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Lert et al.

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(54) **AUTONOMOUS TRANSPORTS FOR STORAGE AND RETRIEVAL SYSTEMS**

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See application file for complete search history.

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(57) **ABSTRACT**

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An autonomous transport vehicle for transferring case units to and from predefined storage areas in an automated case unit storage system, the automated case unit storage system including an array of multilevel storage racks with picking aisles passing therebetween and at least one multilevel vertical conveyor having movable shelves, the autonomous transport vehicle including a frame configured to traverse the picking aisles and a transfer deck connecting the picking aisles to the at least one multilevel vertical conveyor for transferring case units between the predefined storage areas and the at least one multilevel vertical conveyor, and a controller connected to the frame, the controller being configured to effect movement of the autonomous transport vehicle through the picking aisles for accessing each storage area within a respective level of the array of multilevel storage racks and each shelf of the at least one multilevel vertical conveyor.

Related U.S. Application Data

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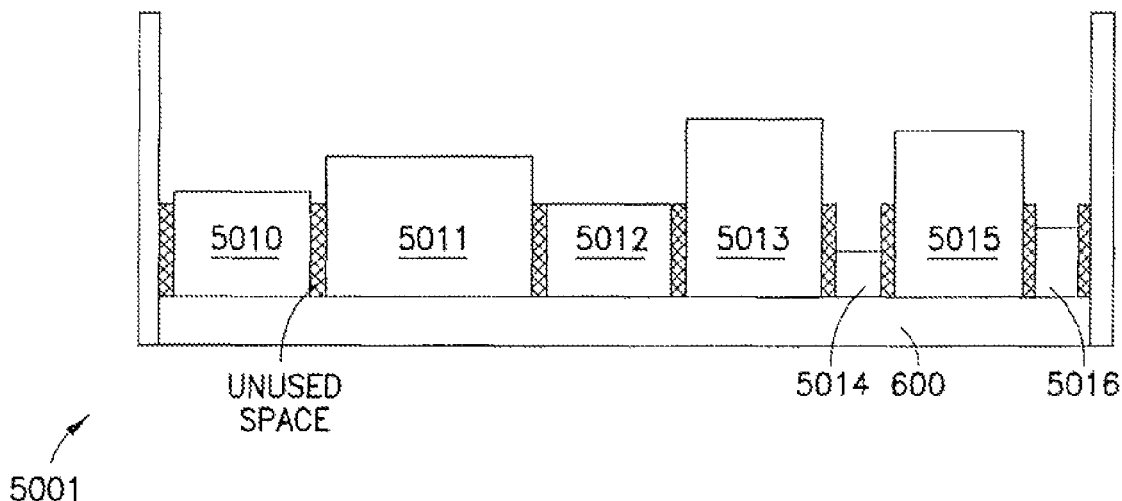
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(58) **Field of Classification Search**
CPC B65G 1/0492; B65G 1/065; Y10S 901/01

9 Claims, 23 Drawing Sheets



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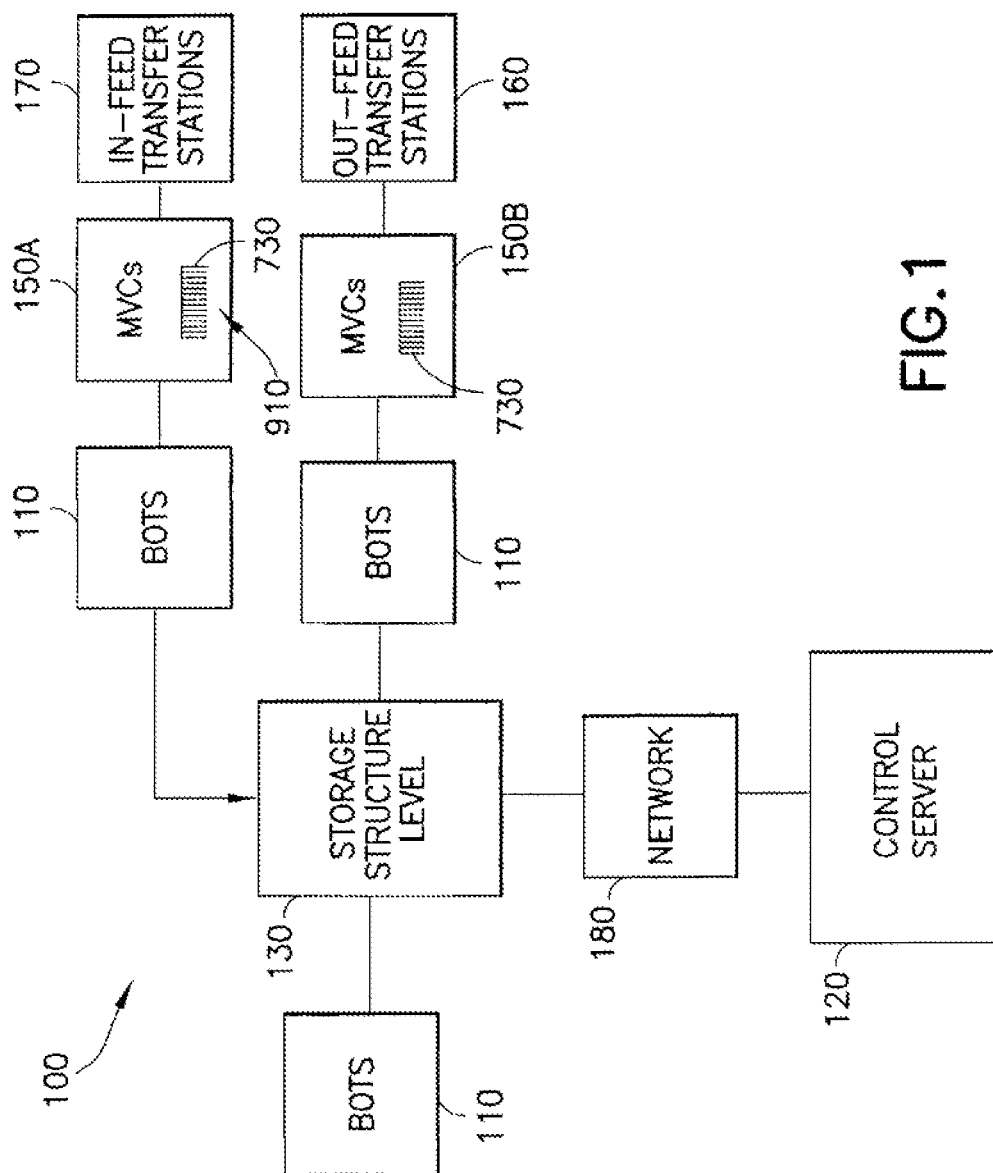
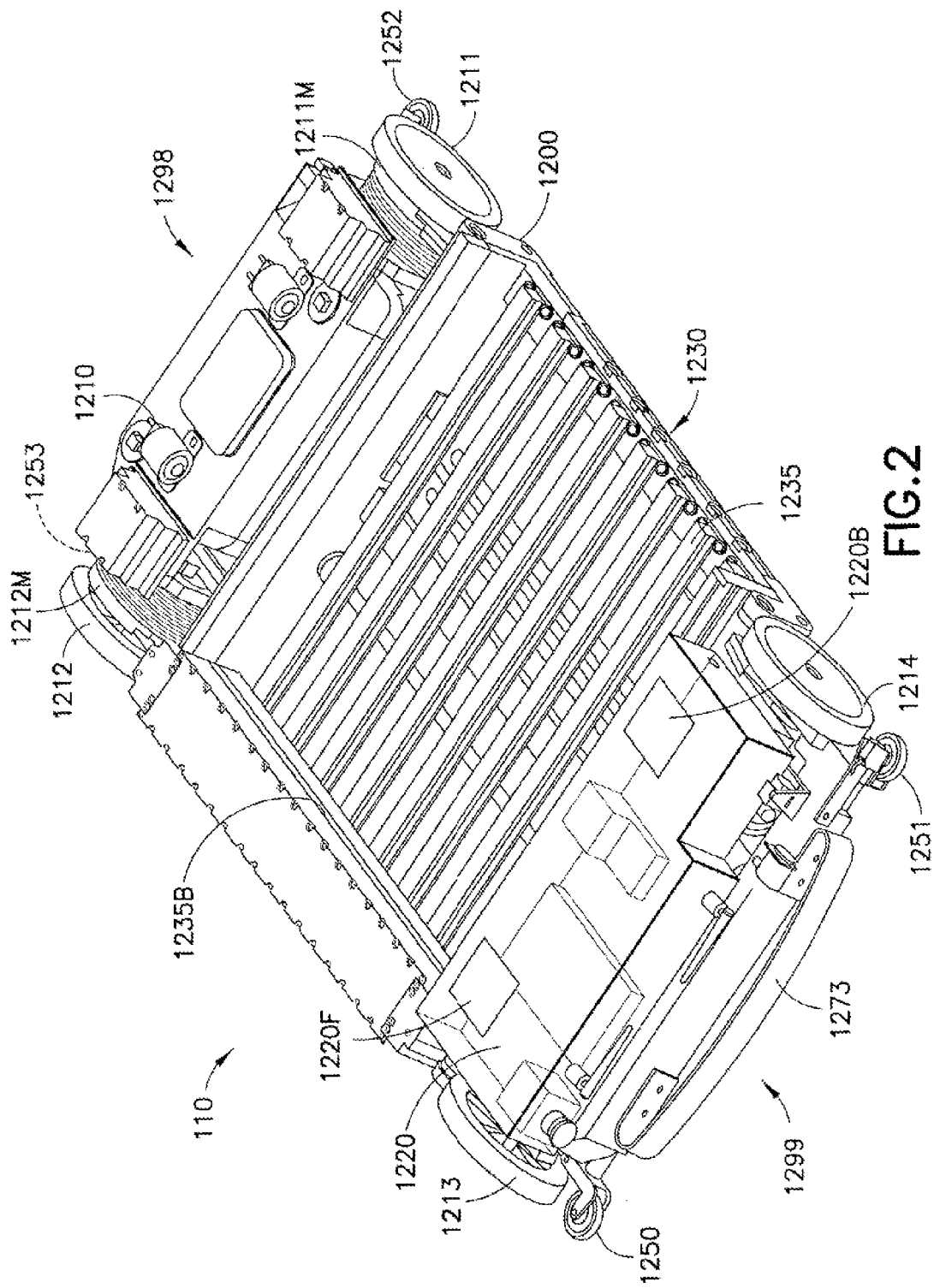


FIG. 1



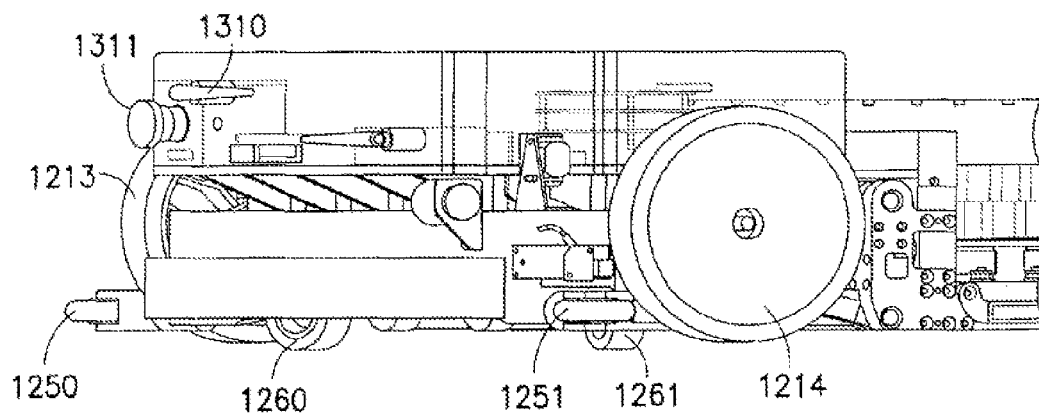


FIG. 3A

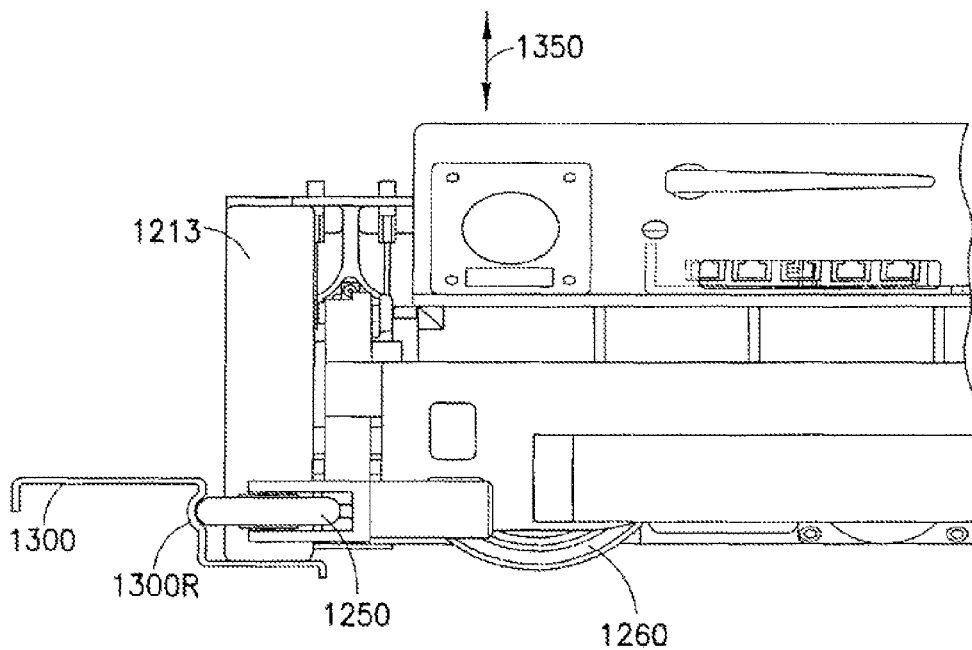


FIG. 3B

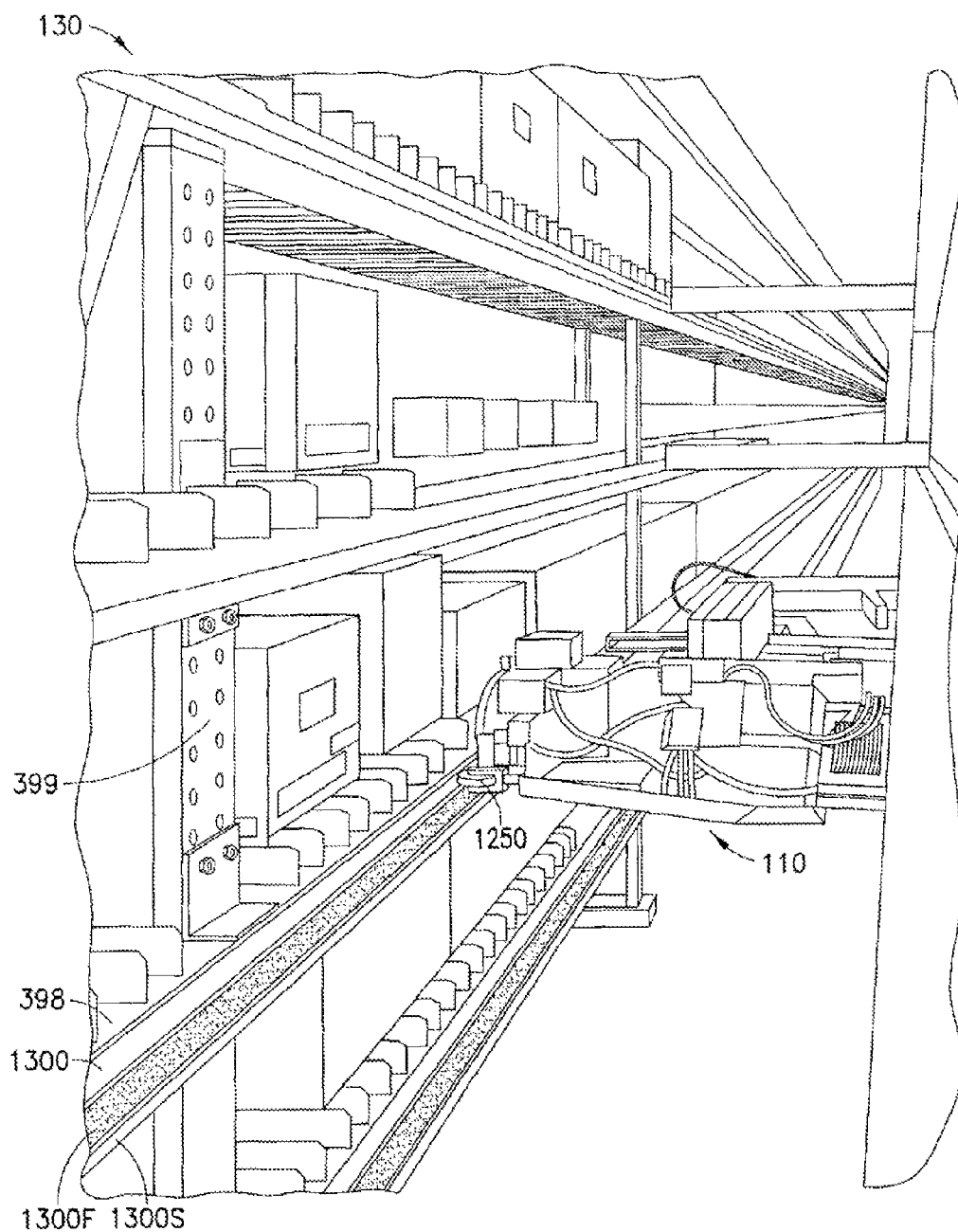


FIG. 3C

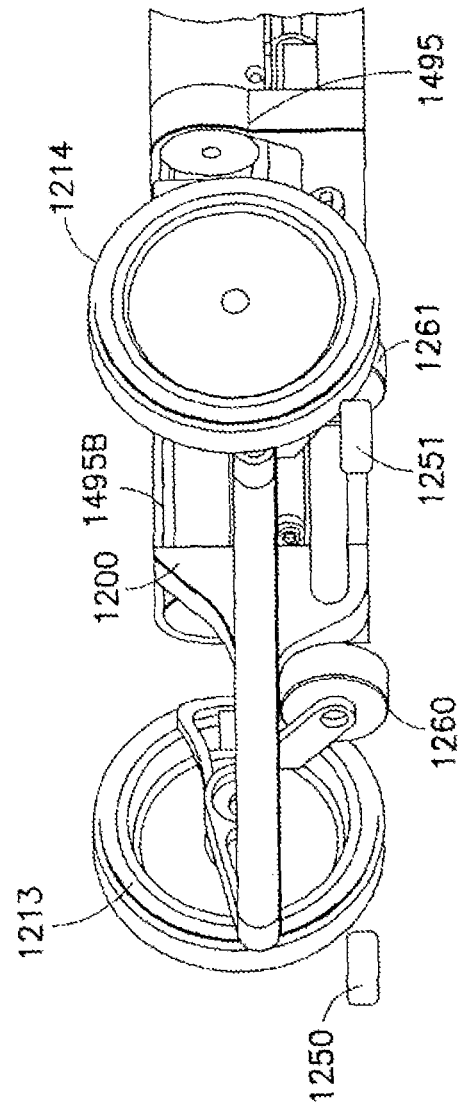


FIG. 4A

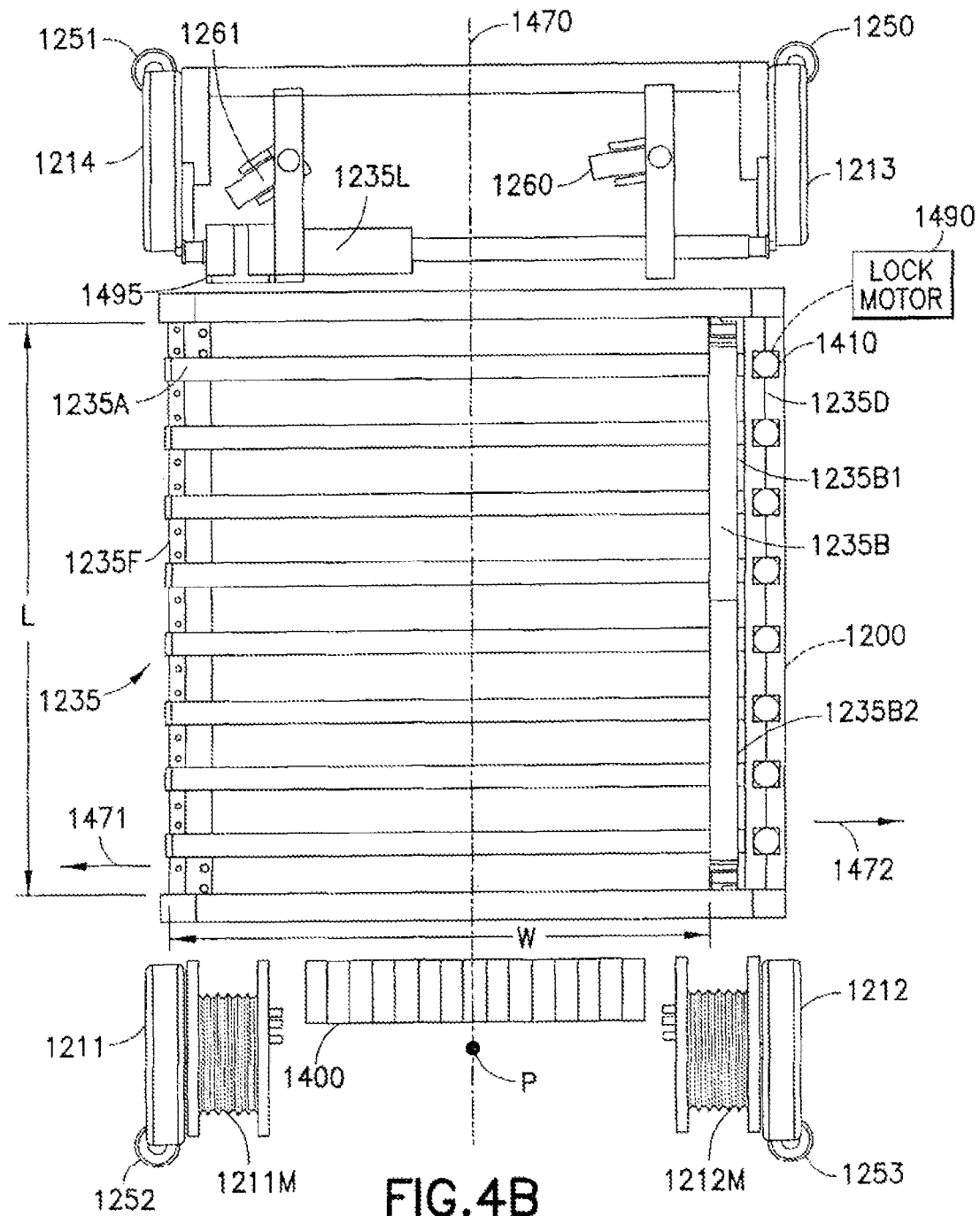


FIG. 4B

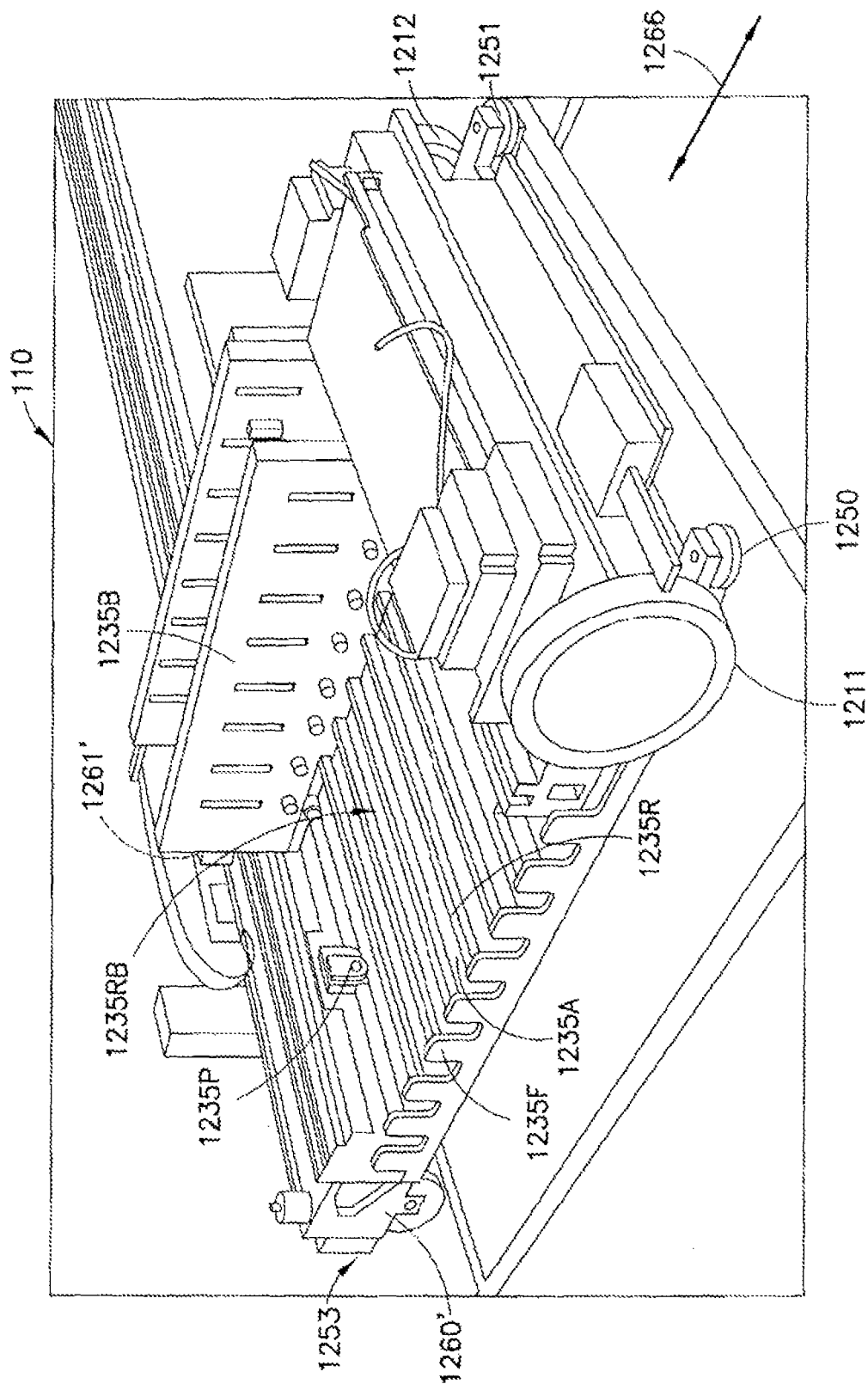
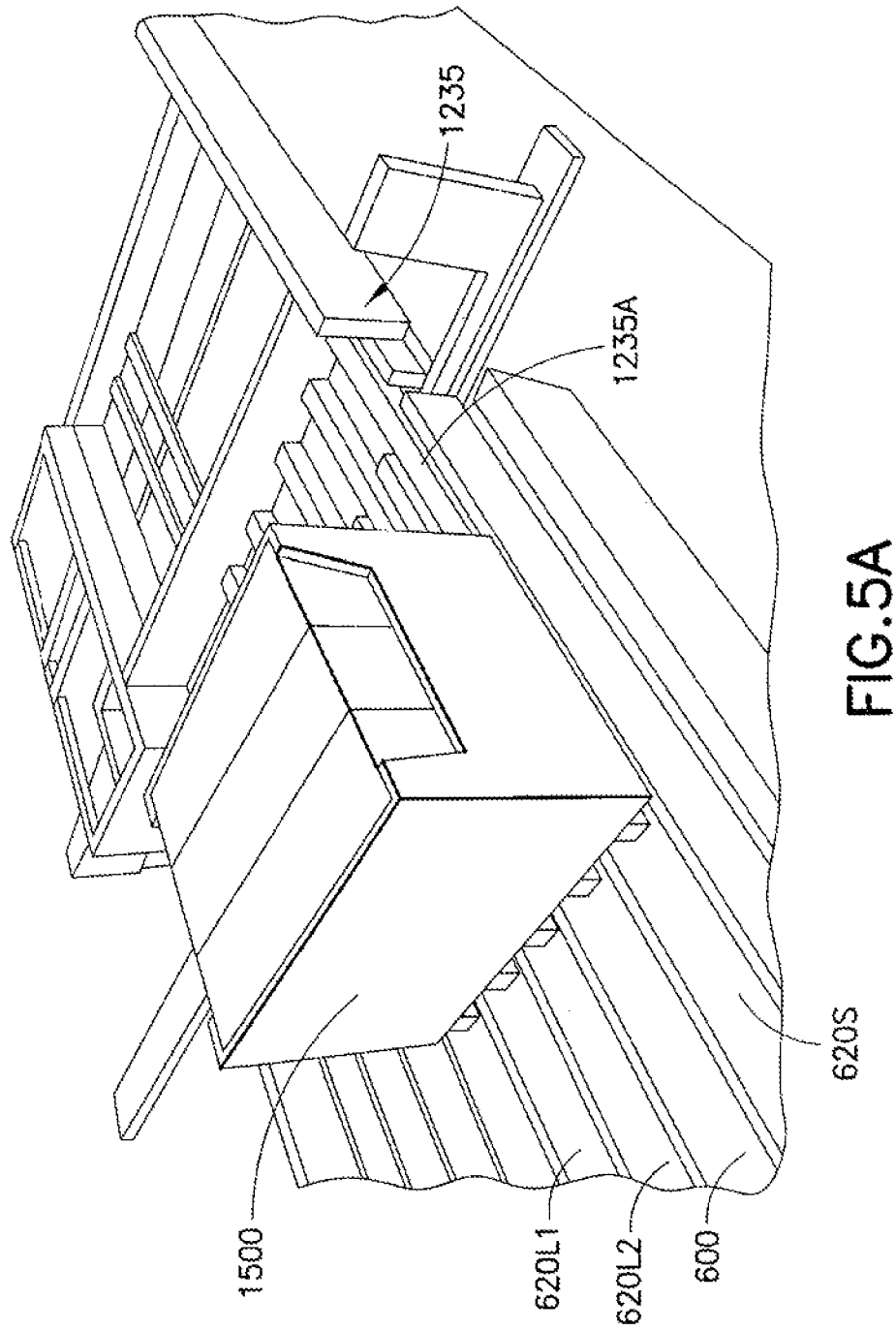


FIG. 4C



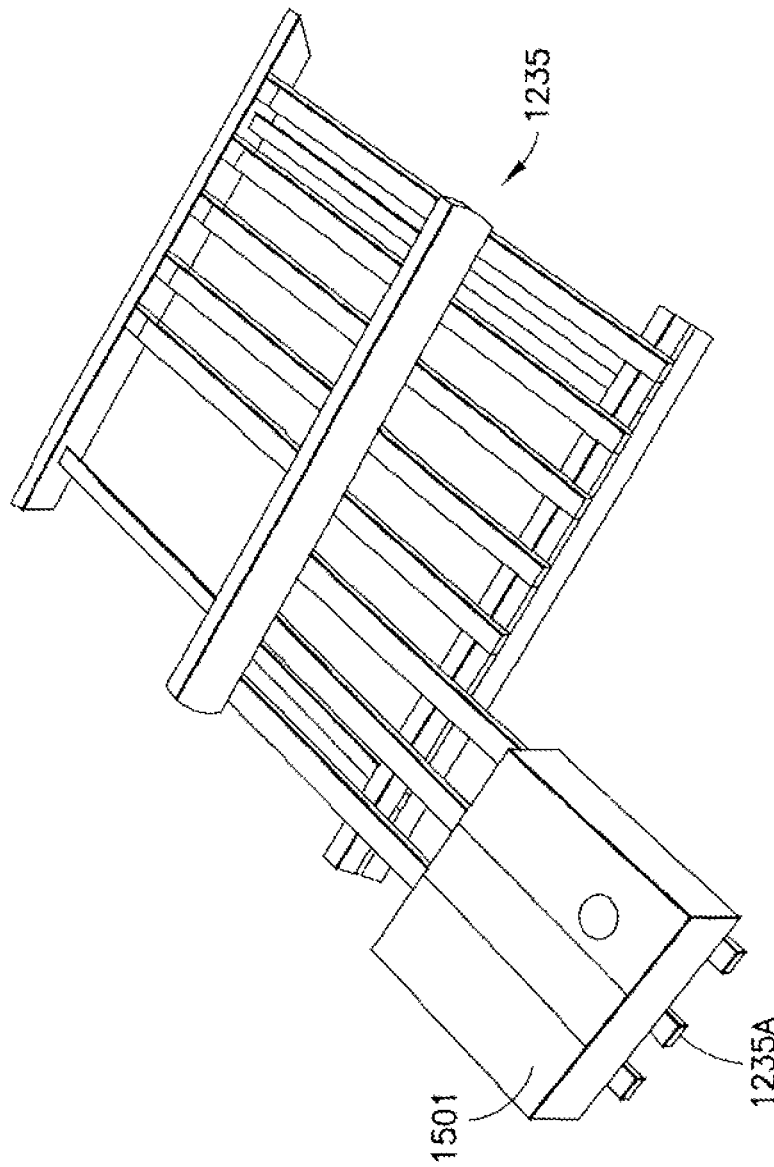
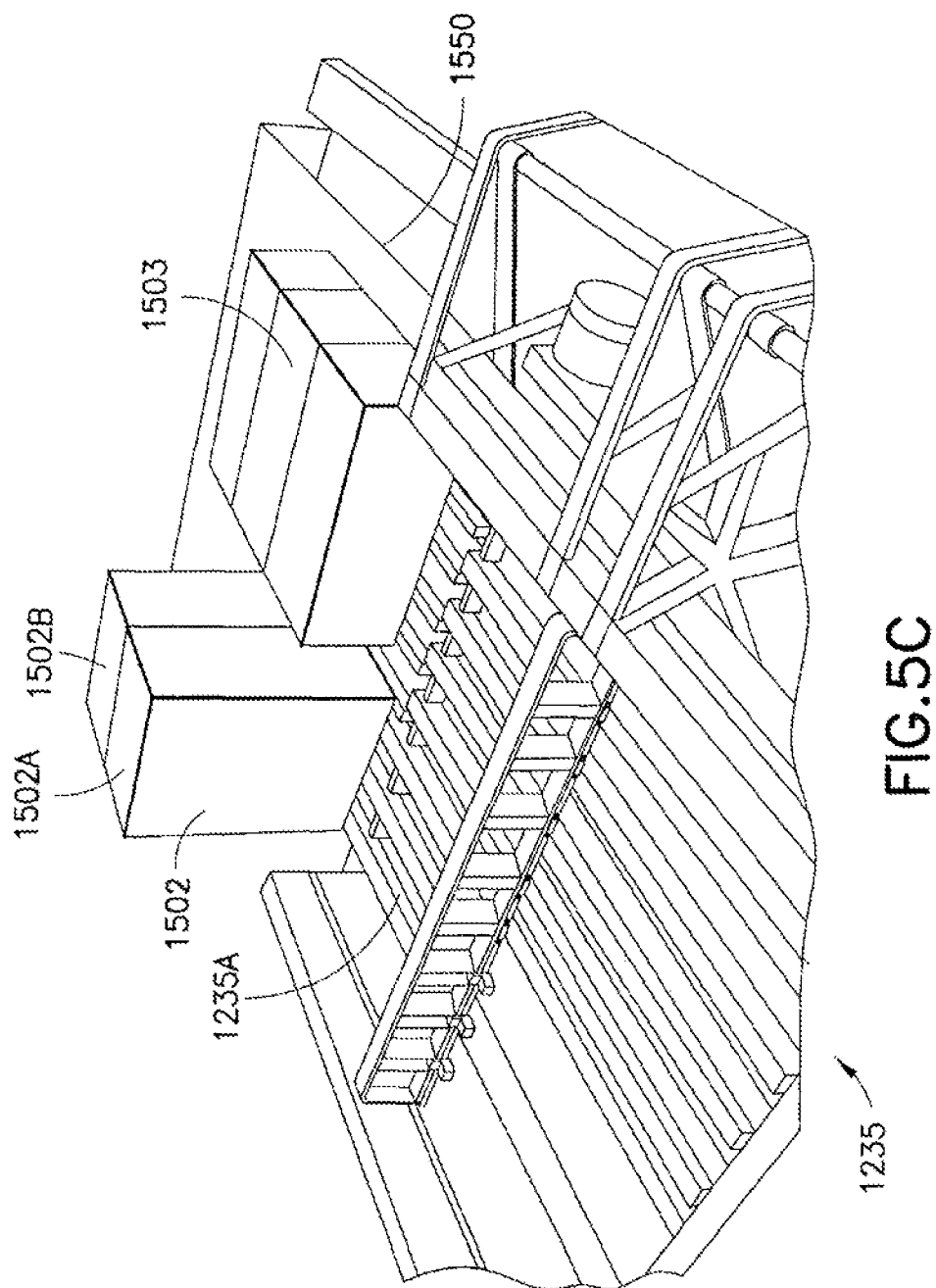


FIG. 5B



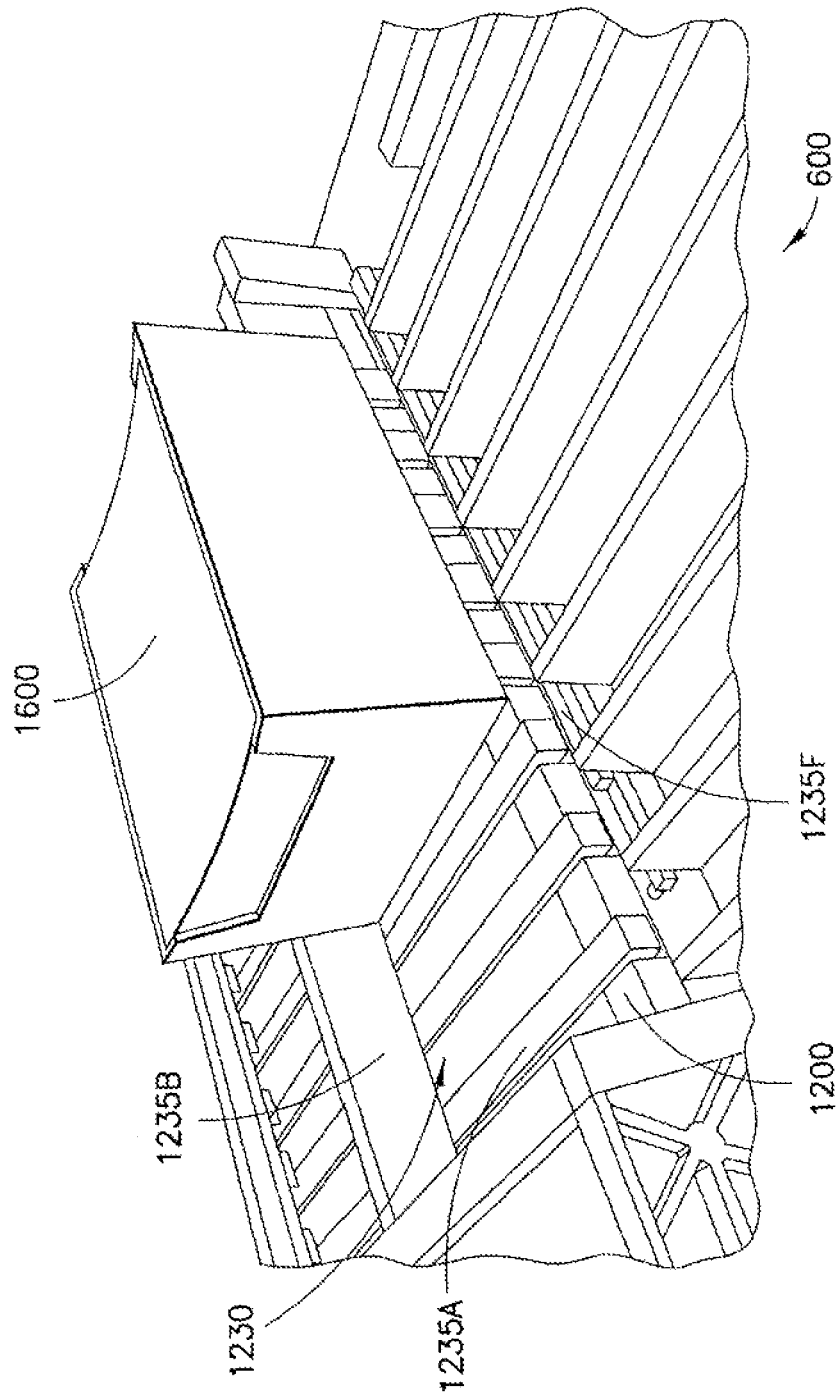


FIG. 6A

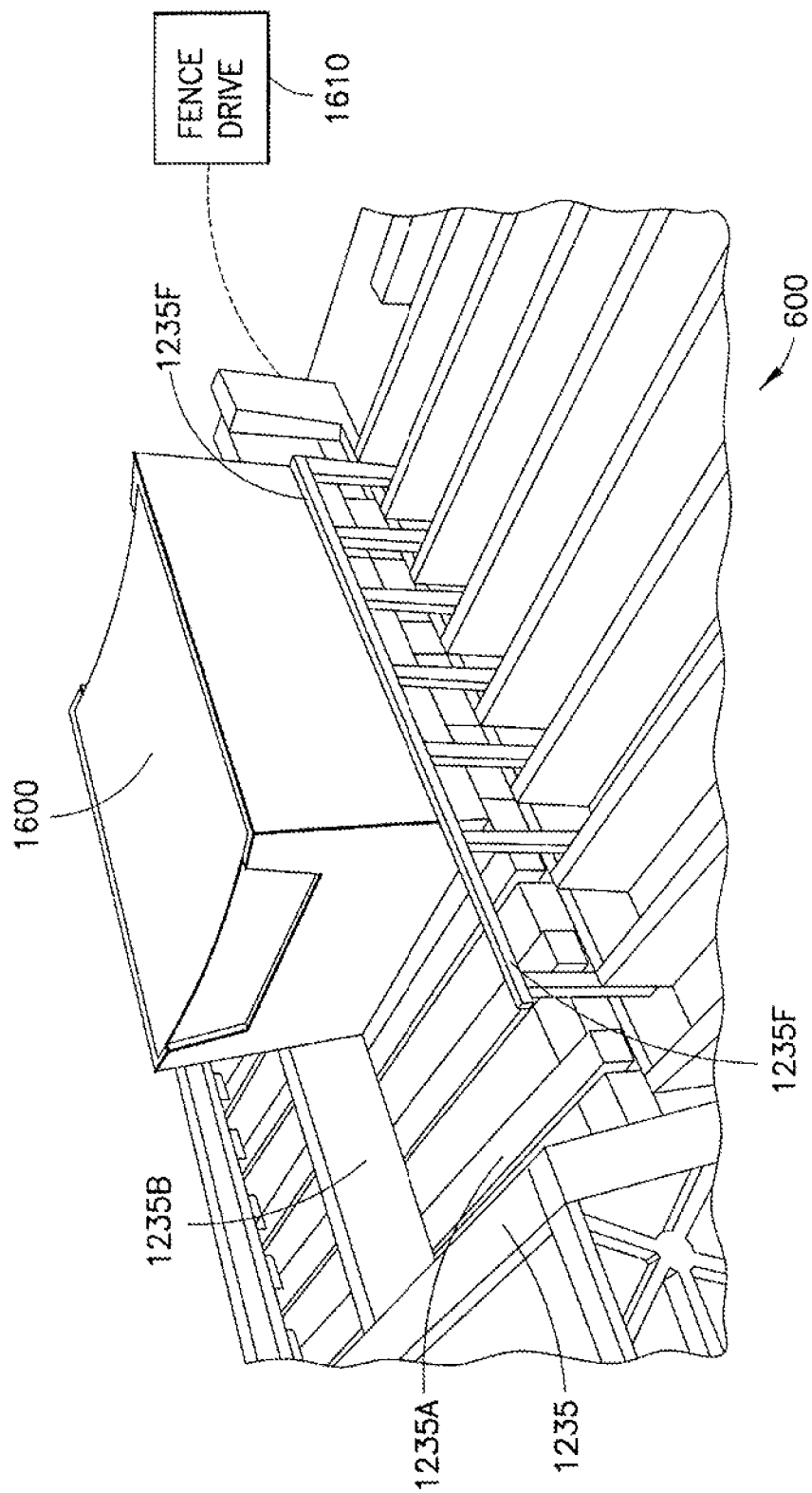


FIG. 6B

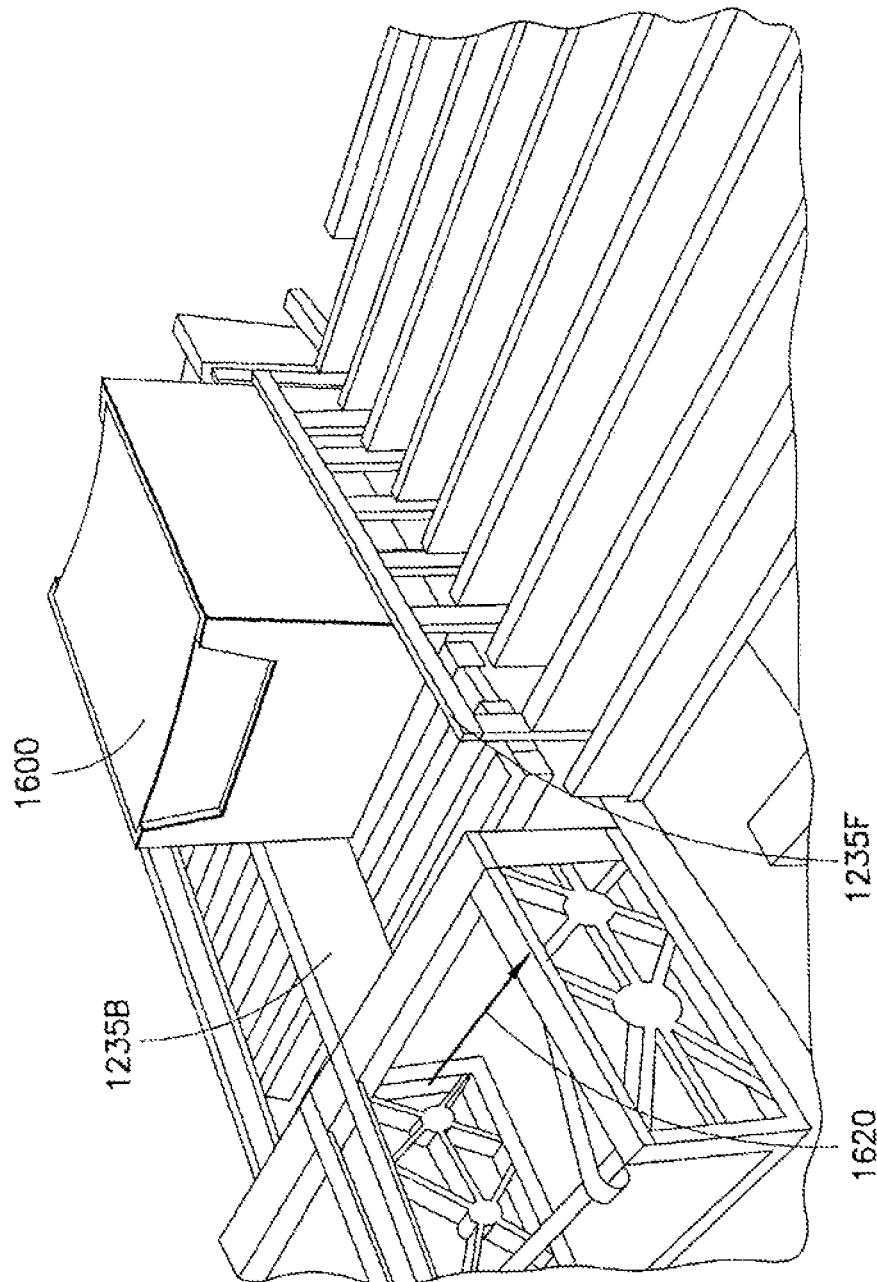


FIG. 6C

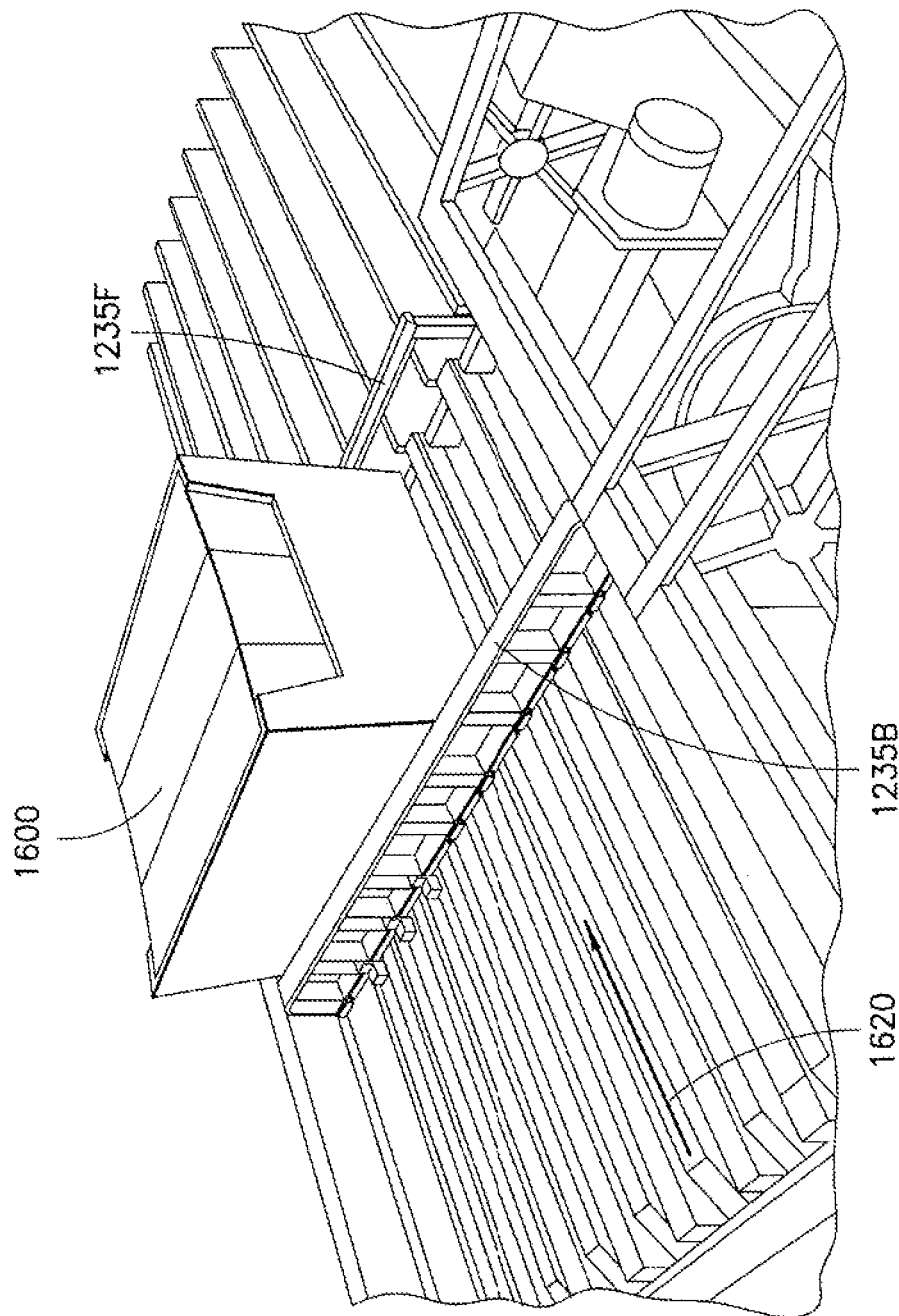


FIG. 6D

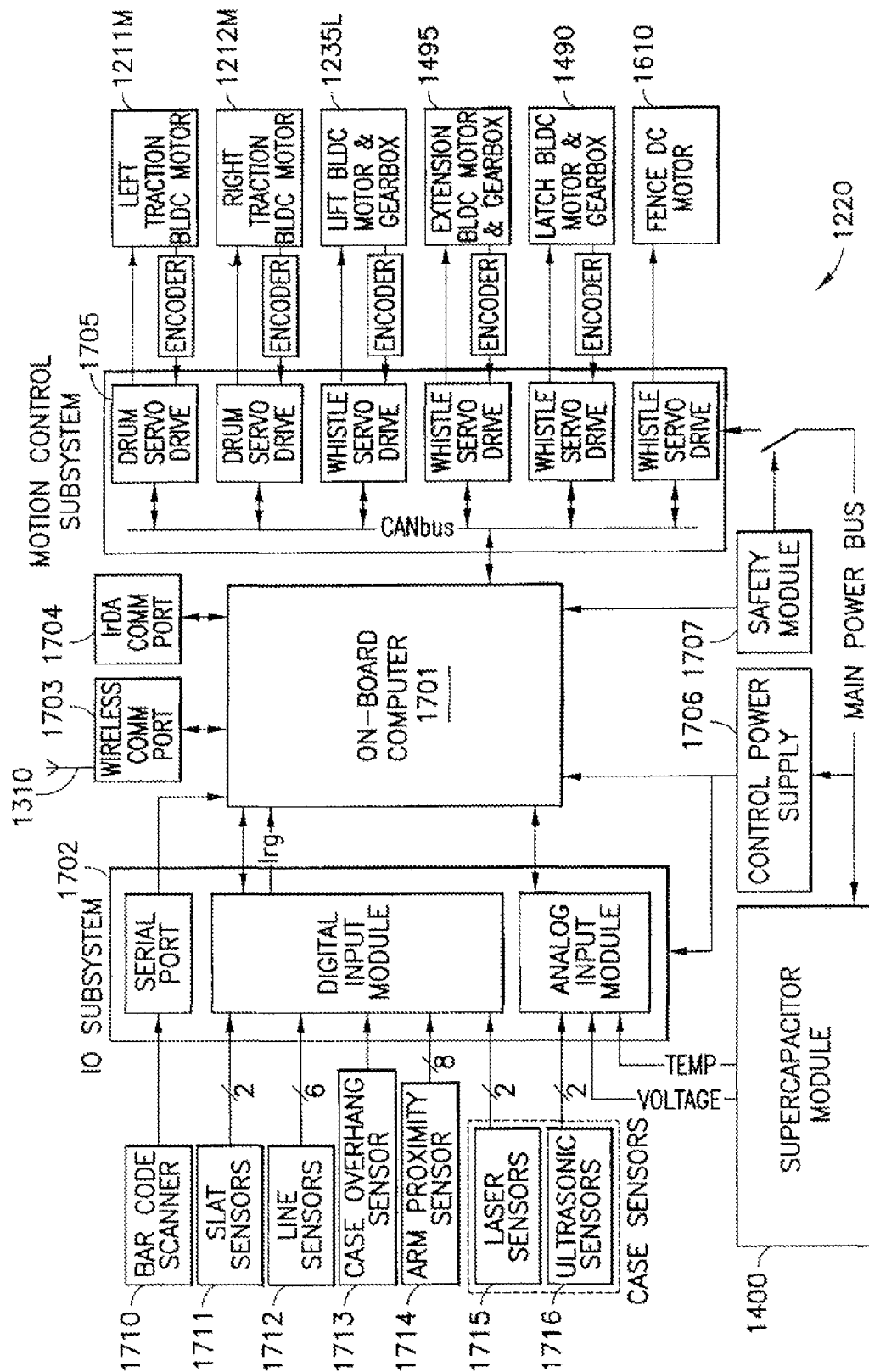


FIG. 7

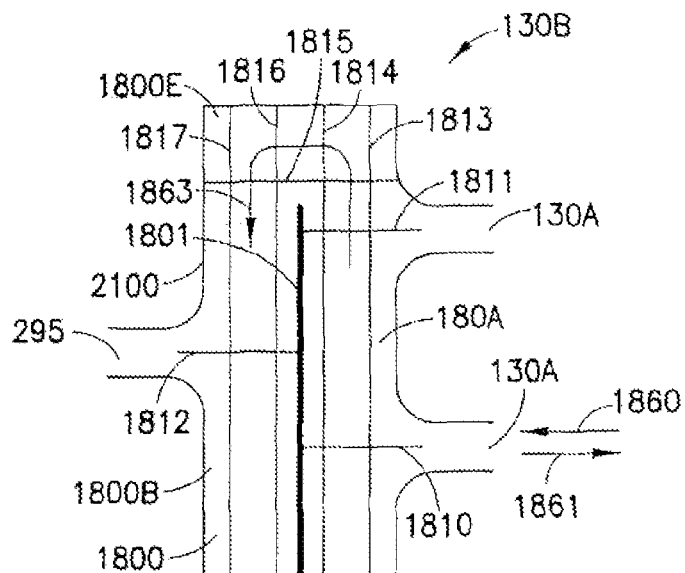


FIG. 8

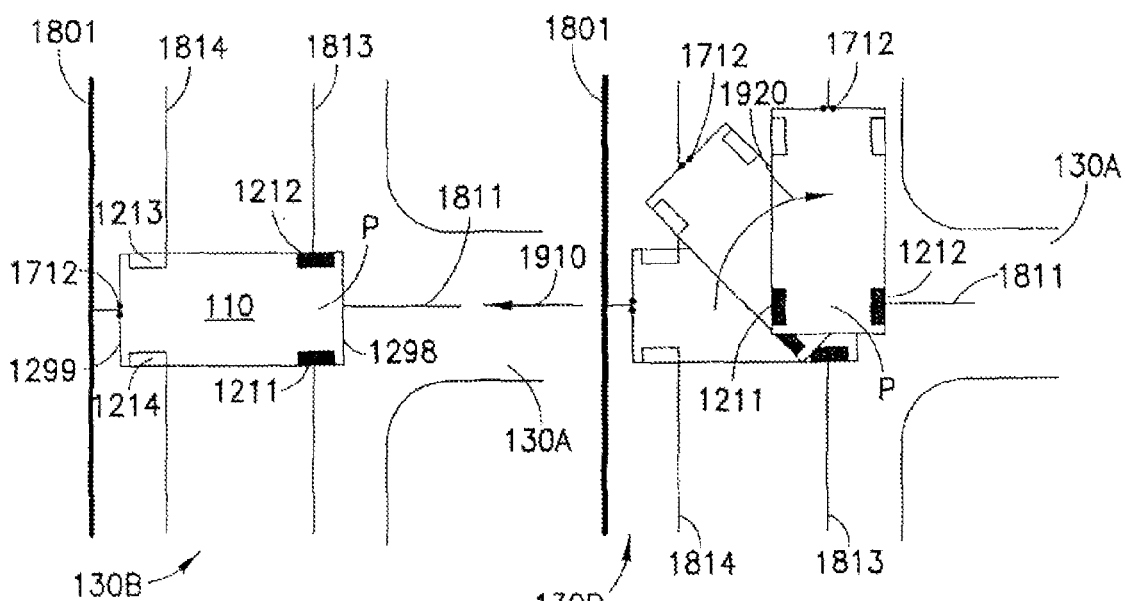


FIG. 9A

FIG. 9B

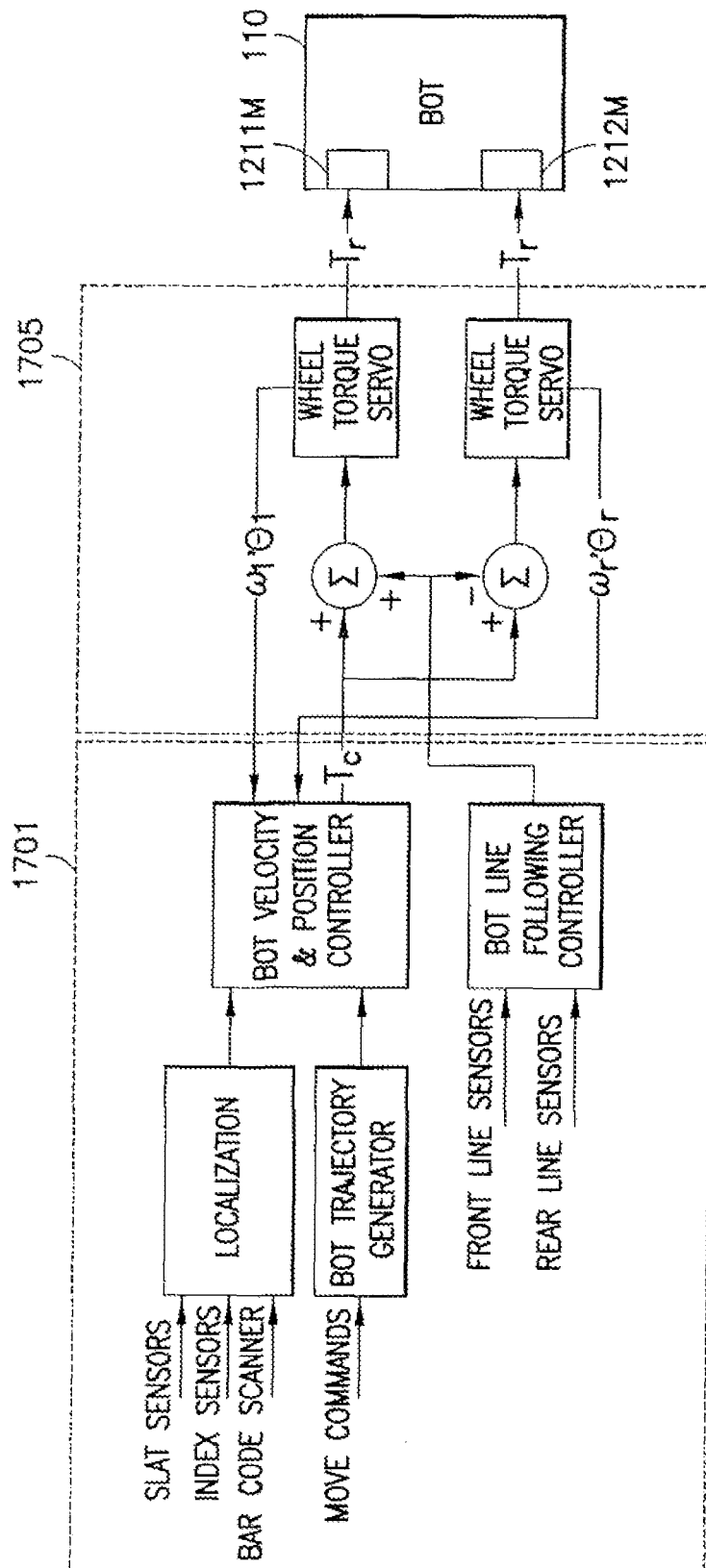


FIG.10

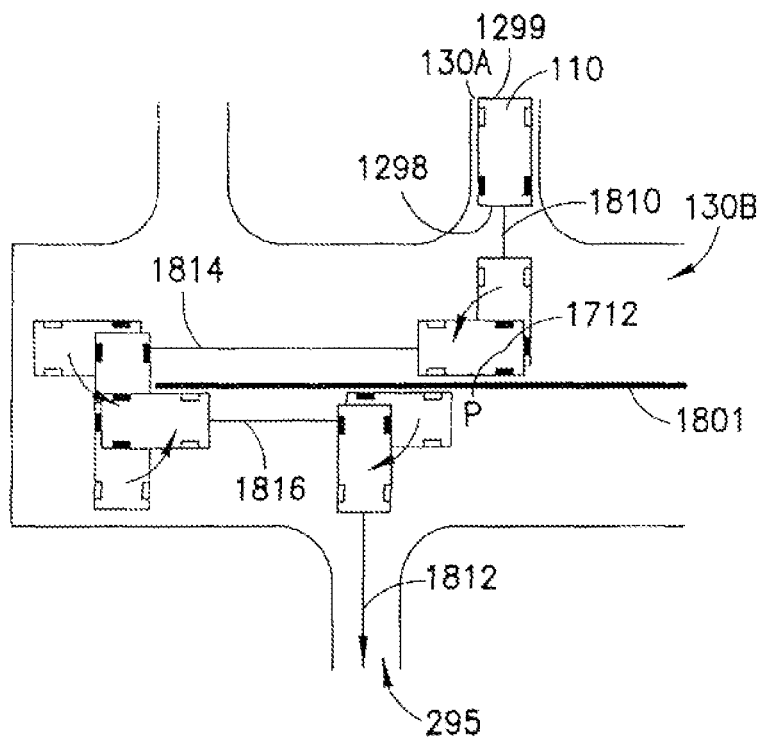


FIG. 11A

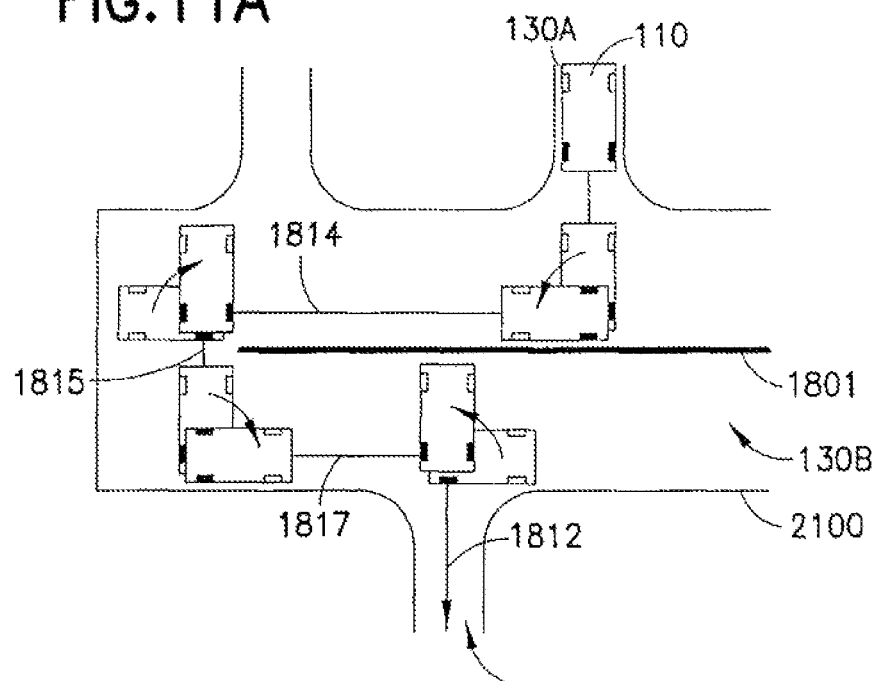


FIG. 11B

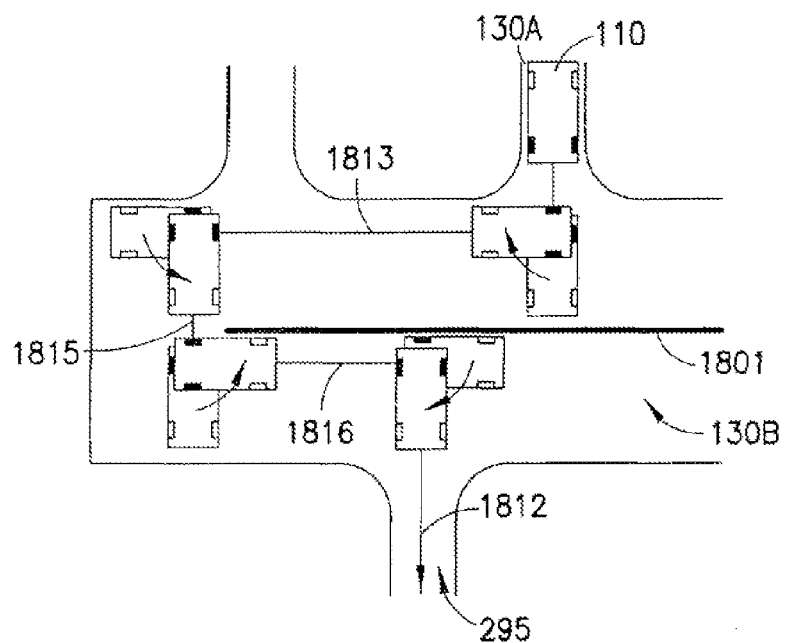


FIG. 11C

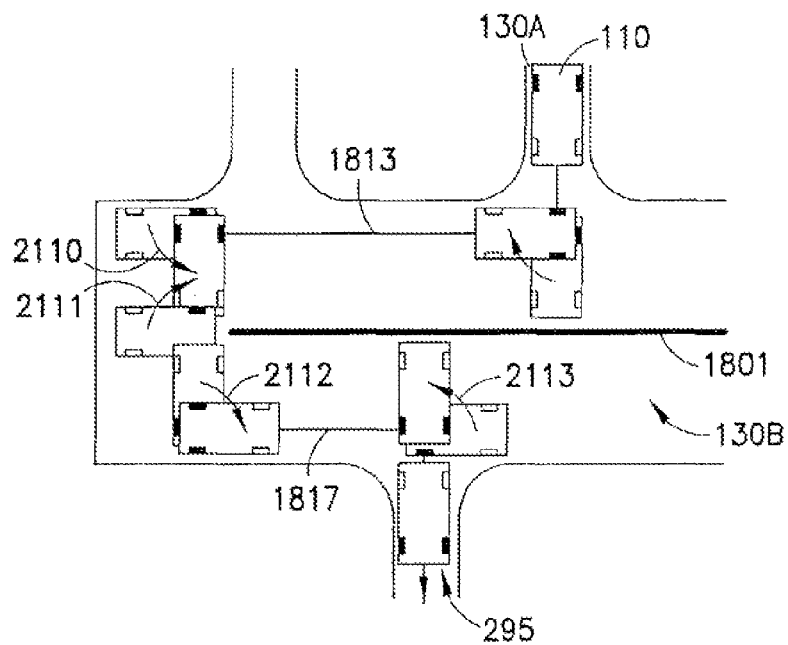


FIG. 11D

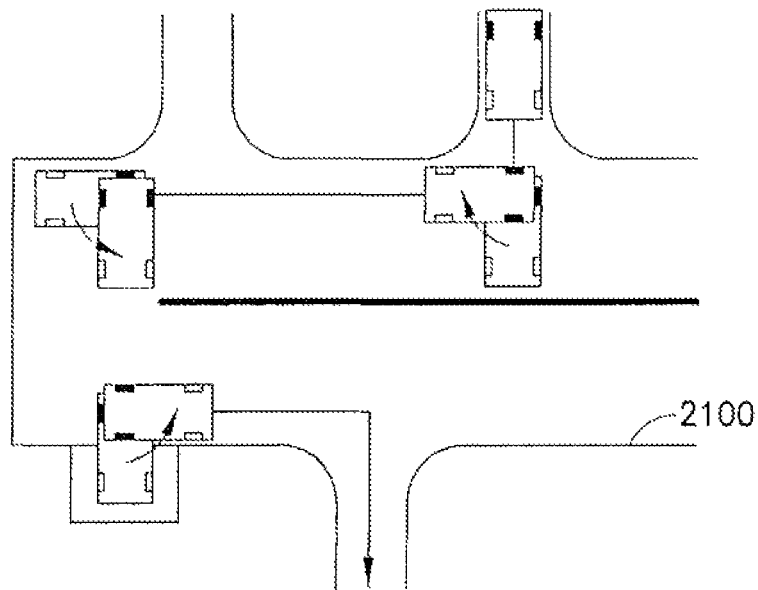


FIG. 11E

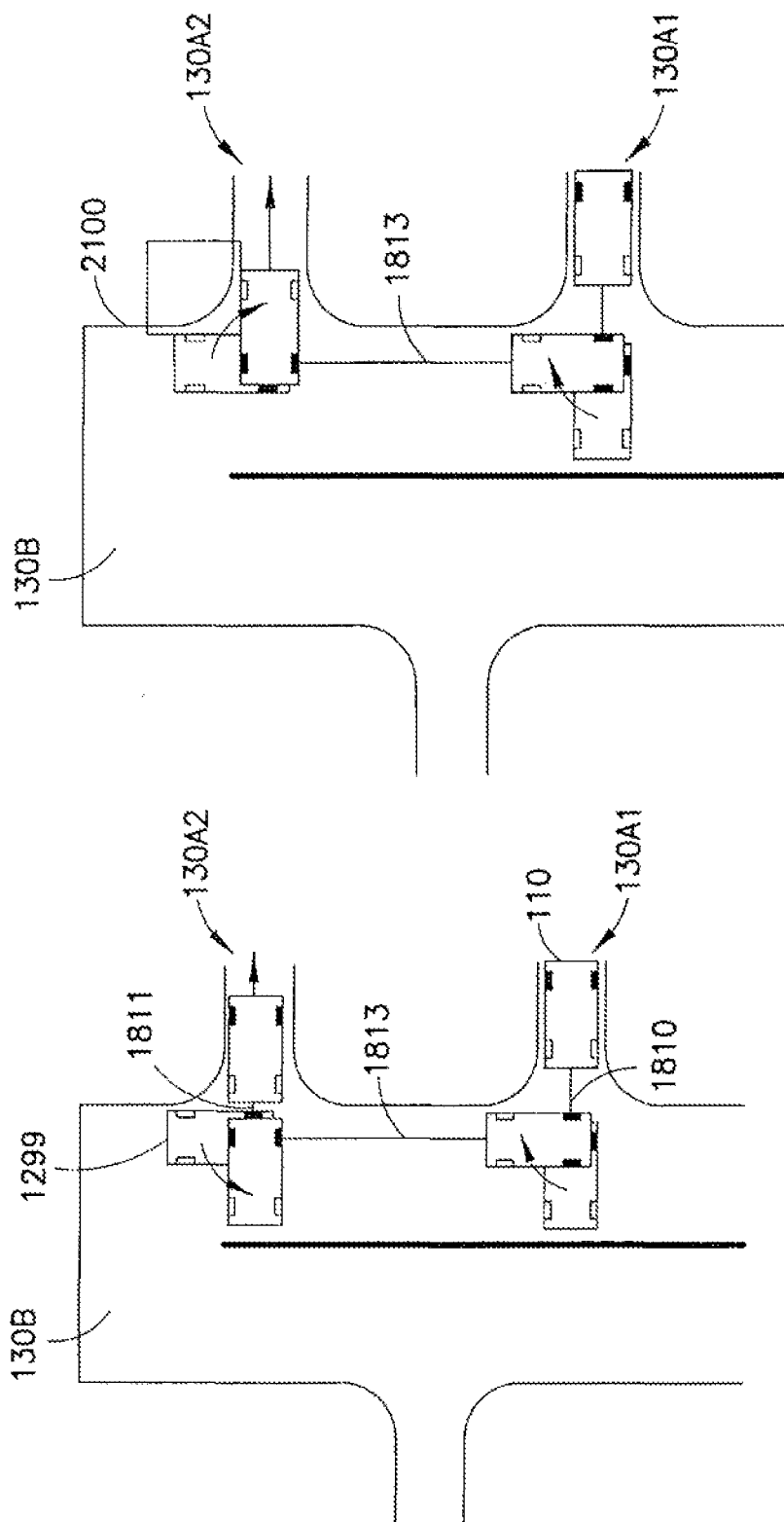
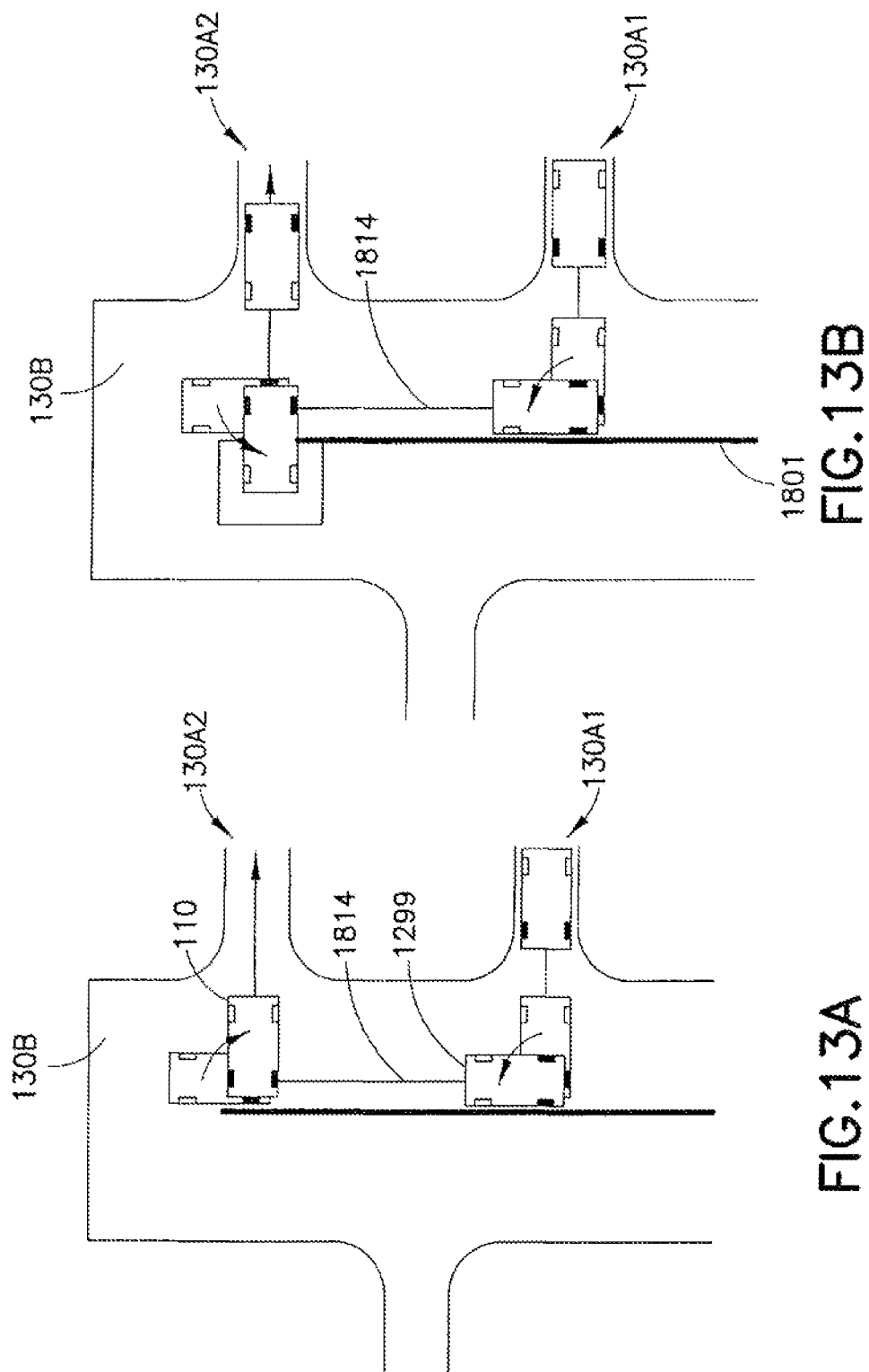
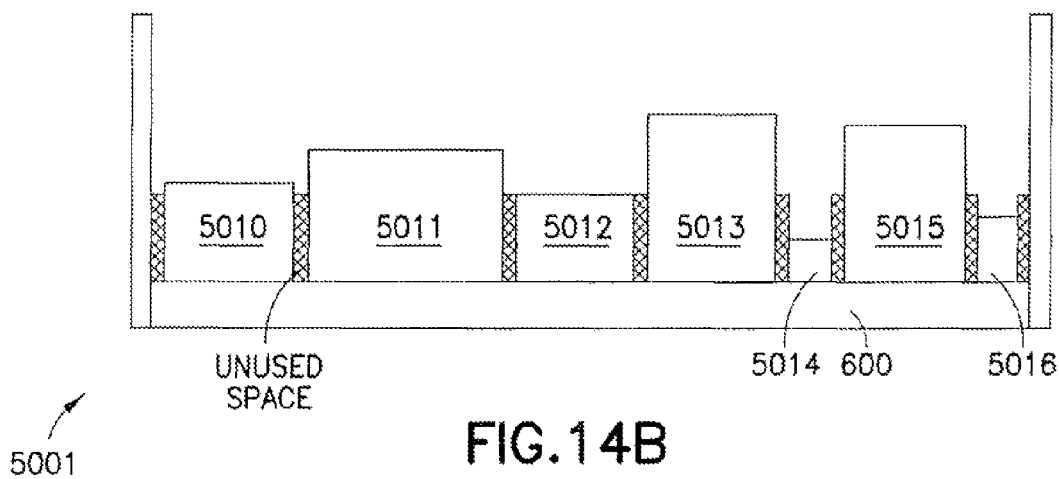
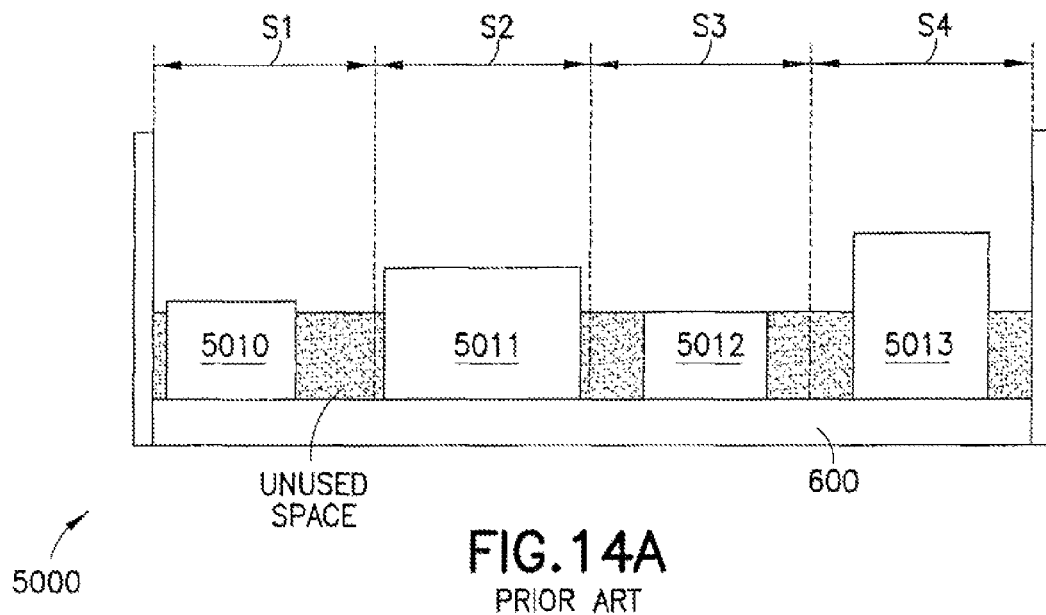


FIG. 12B

FIG. 12A





UNUSED STORAGE SPACE (DYNAMIC ALLOCATION) = 

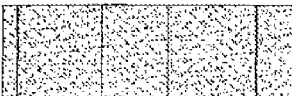
UNUSED STORAGE SPACE (STORAGE SLOTS) = 

FIG. 14C

AUTONOMOUS TRANSPORTS FOR STORAGE AND RETRIEVAL SYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 12/757,312 filed on Apr. 10, 2010 and claims the benefit of U.S. Provisional Patent Application No. 61/168,349 filed on Apr. 10, 2009, the disclosure of which is incorporated herein by reference in its entirety.

This application is related to U.S. patent application Ser. No. 12/757,381, entitled "STORAGE AND RETRIEVAL SYSTEM," filed on Apr. 9, 2010; U.S. patent application Ser. No. 12/757,337, entitled "CONTROL SYSTEM FOR STORAGE AND RETRIEVAL SYSTEMS," filed on Apr. 9, 2010; U.S. patent application Ser. No. 12/757,354, entitled "LIFT INTERFACE FOR STORAGE AND RETRIEVAL SYSTEMS," filed on Apr. 9, 2010; and U.S. patent application Ser. No. 12/757,220, entitled "STORAGE AND RETRIEVAL SYSTEM," filed on Apr. 9, 2010, the disclosures of which are incorporated by reference herein in their entireties.

BACKGROUND

1. Field

The exemplary embodiments generally relate to material handling systems and, more particularly, to transports for automated storage and retrieval systems.

2. Brief Description of Related Developments

Warehouses for storing case units may generally comprise a series of storage racks that are accessible by transport devices such as, for example, fork lifts, carts and elevators that are movable within aisles between or along the storage racks or by other lifting and transporting devices. These transport devices may be automated or manually driven. Generally the items transported to/from and stored on the storage racks are contained in carriers, for example storage containers such as trays, totes or shipping cases, or on pallets. Generally, incoming pallets to the warehouse (such as from manufacturers) contain shipping containers (e.g. cases) of the same type of goods. Outgoing pallets leaving the warehouse, for example, to retailers have increasingly been made of what may be referred to as mixed pallets. As may be realized, such mixed pallets are made of shipping containers (e.g. totes or cases such as cartons, etc.) containing different types of goods. For example, one case on the mixed pallet may hold grocery products (soup can, soda cans, etc.) and another case on the same pallet may hold cosmetic or household cleaning or electronic products. Indeed some cases may hold different types of products within a single case. Conventional warehousing systems, including conventional automated warehousing systems do not lend themselves to efficient generation of mixed goods pallets. In addition, storing case units in, for example carriers or on pallets generally does not allow for the retrieval of individual case units within those carriers or pallets without transporting the carriers or pallets to a workstation for manual or automated removal of the individual items.

It would be advantageous to have a storage and retrieval system for efficiently storing and retrieving individual case units without containing those case units in a carrier or on a pallet.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and other features of the disclosed embodiments are explained in the following description, taken in connection with the accompanying drawings, wherein:

FIG. 1 schematically illustrates an exemplary storage and retrieval system in accordance with an exemplary embodiment;

FIGS. 2 and 3A-3C illustrate a transport robot in accordance with an exemplary embodiment;

FIGS. 4A and 4B illustrate partial schematic views of the transport robot of FIGS. 2, 3A and 3B in accordance with an exemplary embodiment;

FIG. 4C illustrates a schematic view of a transport robot in accordance with an exemplary embodiment;

FIGS. 5A-5C and 6A-6D illustrate a portion of a transfer arm of the transport robot of FIGS. 12, 13A and 13B in accordance with an exemplary embodiment;

FIG. 7 schematically illustrates a control system of the transport robot of FIGS. 2, 3A and 3B in accordance with an exemplary embodiment;

FIGS. 8, 9A and 9B schematically illustrate exemplary operational paths of a transport robot in accordance with the exemplary embodiments;

FIG. 10 schematically illustrates a portion of the control system of FIG. 17 in accordance with an exemplary embodiment;

FIGS. 11A-11E, 12A, 12B, 13A and 13B schematically illustrate exemplary operational paths of a transport robot in accordance with the exemplary embodiments;

FIG. 14A illustrates a conventional organization of item storage in a storage bay;

FIG. 14B illustrates an organization of items in a storage bay in accordance with an exemplary embodiment; and

FIG. 14C illustrates a comparison of unused storage space between the item storage of FIG. 14A and the item storage of FIG. 14B.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENT(S)

FIG. 1 generally schematically illustrates a storage and retrieval system 100 in accordance with an exemplary embodiment. Although the embodiments disclosed will be described with reference to the embodiments shown in the drawings, it should be understood that the embodiments disclosed can be embodied in many alternate forms. In addition, any suitable size, shape or type of elements or materials could be used.

In accordance with one exemplary embodiment the storage and retrieval system 100 may operate in a retail distribution center or warehouse to, for example, fulfill orders received from retail stores for case units (where case units as used herein means items not stored in trays, on totes or on pallets, e.g. uncontained). It is noted that the case units may include cases of items (e.g. case of soup cans, boxes of cereal, etc.) or individual items that are adapted to be taken off of or placed on a pallet. In accordance with the exemplary embodiments, shipping cases or case units (e.g. cartons, barrels, boxes, crates, jugs, or any other suitable device for holding items) may have variable sizes and may be used to hold items in shipping and may be configured so they are capable of being palletized for shipping. It is noted that when, for example, pallets of items arrive at the storage and retrieval system the content of each pallet may be uniform (e.g. each pallet holds a predetermined number of the same item—one pallet holds

soup and another pallet holds cereal) and as pallets leave the storage and retrieval system the pallets may contain any suitable number and combination of different items (e.g. each pallet may hold different types of items—a pallet holds a combination of soup and cereal). In alternate embodiments the storage and retrieval system described herein may be applied to any environment in which items are stored and retrieved.

The storage and retrieval system **100** may be configured for installation in, for example, existing warehouse structures or adapted to new warehouse structures. In one exemplary embodiment, the storage and retrieval system **100** may include in-feed and out-feed transfer stations **170**, **160**, multilevel vertical conveyors **150A**, **150B**, a storage structure **130**, and a number of autonomous vehicular transport robots **110** (referred to herein as “bots”). In alternate embodiments the storage and retrieval system may also include robot or bot transfer stations (as described in, for example, U.S. patent application Ser. No. 12/757,220, entitled “STORAGE AND RETRIEVAL SYSTEM,” previously incorporated by reference herein) that may provide an indirect interface between the bots and the multilevel vertical conveyor **150A**, **150B**. The in-feed transfer stations **170** and out-feed transfer stations **160** may operate together with their respective multilevel vertical conveyors **150A**, **150B** for transferring items to and from one or more levels of the storage structure **130**. The multilevel vertical conveyors may be substantially similar to those described in U.S. patent application Ser. No. 12/757,354, entitled “LIFT INTERFACE FOR STORAGE AND RETRIEVAL SYSTEMS,” previously incorporated by reference herein in its entirety. It is noted that while the multilevel vertical conveyors are described herein as being dedicated inbound conveyors **150A** and outbound conveyors **150B**, in alternate embodiments each of the conveyors **150A**, **150B** may be used for both inbound and outbound transfer of case units/items from the storage and retrieval system. The bots **110** may be configured to place items, such as the above described retail merchandise, into picking stock in the one or more levels of the storage structure **130** and then selectively retrieve ordered items for shipping the ordered items to, for example, a store or other suitable location. In one exemplary embodiment, the bots **110** may interface directly with the multilevel vertical conveyors **150A**, **150B** through, for example, access provided by transfer areas **295** (FIGS. 8 and 11A-11E) while in other exemplary embodiments, the bots **110** may interface indirectly with the respective multilevel vertical conveyors **150A**, **150B** in any suitable manner such as through bot transfer stations.

The storage structure **130** may be substantially similar to the storage structure described in U.S. patent application Ser. No. 12/757,381, entitled “STORAGE AND RETRIEVAL SYSTEM,” and U.S. patent application Ser. No. 12/757,220, entitled “STORAGE AND RETRIEVAL SYSTEM,” previously incorporated herein by reference in their entirety. For example, the storage structure **130** may include multiple levels of storage rack modules, where each level includes picking aisles **130A** (FIGS. 8-9D) that provide access to the storage racks, transfer decks **130B** (FIGS. 8-9D) that provide access to the picking aisles, and charging stations (not shown) that are configured to replenish, for example, a battery pack of the bots **110**. The bots **110** and other suitable features of the storage and retrieval system **100** may be controlled by, for example, one or more central system control computers (e.g. control server) **120** through, for example, any suitable network **180**. In one example, the central control computer and network may be substantially similar to those described in U.S. patent application Ser. No. 12/757,354, entitled “LIFT

INTERFACE FOR STORAGE AND RETRIEVAL SYSTEMS,” U.S. patent application Ser. No. 12/757,381, entitled “STORAGE AND RETRIEVAL SYSTEM,”; U.S. patent application Ser. No. 12/757,220, entitled “STORAGE AND RETRIEVAL SYSTEM,”; and U.S. patent application Ser. No. 12/757,337, entitled “CONTROL SYSTEM FOR STORAGE AND RETRIEVAL SYSTEMS,” previously incorporated by reference herein in their entirety. The network **180** may be a wired network, a wireless network or a combination of a wireless and wired network using any suitable type and/or number of communication protocols. It is noted that, in one exemplary embodiment, the system control server **120** may be configured to manage and coordinate the overall operation of the storage and retrieval system **100** and interface with, for example, a warehouse management system, which in turn manages the warehouse facility as a whole.

As an exemplary operation of an order fulfillment process of the storage and retrieval system **100**, case units for replenishing the picking stock are input at, for example, depalletizing workstations so that case units bundled together on pallets (or other suitable container-like transport supports) are separated and individually carried on, for example, conveyors or other suitable transfer mechanisms (e.g. manned or automated carts, etc.) to the in-feed transfer stations **170**. The in-feed transfer stations **170** assembles the case units into pickfaces (e.g. one or more case units that may form a bot load) and loads the pickfaces onto respective multilevel vertical conveyors **150A**, which carry the pickfaces to a predetermined level of the storage structure **130**. Bots **110** located on the predetermined level of the storage structure **130** interface with the multilevel vertical conveyor **150A** at, for example, the transfer areas **295** for removing the pickfaces from the multilevel vertical conveyor **150A**. The bots **110** transfer the pickfaces from the multilevel vertical conveyors **150A** to a predetermined storage module of the storage structure **130**. When an order for individual case units is made the bots **110** retrieve the corresponding pickfaces from a designated storage module of the storage structure **130** and transfer the ordered case units to transfer areas **295** located on a level of the storage structure **130** from which the ordered case units were picked. The bots **110** interfaces with multilevel vertical conveyor **150B** for transferring the pickfaces to the multilevel vertical conveyor **150B**. The multilevel vertical conveyor **150B** transports the ordered case unit(s) of the pickface to the out-feed transfer stations **160** where the individual case units are transported to palletizing workstations by conveyors **230** where the individual case units are placed on outbound pallets (or other suitable container-like transport supports) for shipping to a customer.

As may be realized, the storage and retrieval system **100** may include multiple in-feed and out-feed multilevel vertical conveyors **150A**, **150B** that are accessible by, for example, bots **110** on each level of the storage and retrieval system **100** so that one or more case unit(s), uncontained or without containment (e.g. case unit(s) are not sealed in trays), can be transferred from a multilevel vertical conveyor **150A**, **150B** to each storage space on a respective level and from each storage space to any one of the multilevel vertical conveyors **150A**, **150B** on a respective level. The bots **110** may be configured to transfer the uncontained case units between the storage spaces and the multilevel vertical conveyors with one pick (e.g. substantially directly between the storage spaces and the multilevel vertical conveyors). By way of further example, the designated bot **110** picks the uncontained case unit(s) from a shelf **730** of a multilevel vertical conveyor, transports the uncontained case unit(s) to a predetermined storage area of the storage structure **130** and places the uncontained case

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unit(s) in the predetermined storage area (and vice versa). In one exemplary embodiment, the storage and retrieval system **100** may include a bot positioning system for positioning the bot adjacent the shelves **730** of the multilevel vertical conveyor **150A**, **150B** for picking/placing a desired pickface from a predetermined one of the shelves **730** (e.g. the bot **110** is positioned so as to be aligned with the pickface on the shelf or a position on the shelf designated to receive the pickface). The bot positioning system may also be configured to correlate the extension of the bot transfer arm **1235** with the movement (e.g. speed and location) of the shelves **730** so that the transfer arm **1235** is extended and retracted to remove (or place) pickfaces from predetermined shelves **730** of the multilevel vertical conveyors **150A**, **150B**. It is noted that at least a portion of the bot positioning system may reside within the control system **1220** (FIG. 7) of the bot **110**.

Referring now to FIGS. 2-6D, the bots **110** that transfer loads (e.g. pickfaces formed of at least one case unit) between, for example, the multilevel vertical conveyors **150A**, **150B** and the storage shelves of a respective level of storage structure **130** will be described. It is noted that in one exemplary embodiment the bots **110** may transfer loads directly to and/or from the multilevel vertical conveyors **150A**, **150B** as will be described below, while in alternate embodiments the bots **110** may interface with the multilevel vertical conveyors indirectly such as through the bot transfer stations. In one example, the bots **110** may be configured for substantially continuous operation. For exemplary purposes only, the bots **110** may have a duty cycle of about ninety-five (95) percent. In alternate embodiments the bots may have any suitable duty cycle and operational periods.

As can be seen in FIG. 2, the bots **110** generally include a frame **1200**, a drive system **1210**, a control system **1220**, and a payload area **1230**. The drive system **1210** and control system **1220** may be mounted to the frame in any suitable manner. The frame may form the payload area **1230** and be configured for movably mounting a transfer arm or effector **1235** to the bot **110**.

In one exemplary embodiment, the drive system **1210** may include two drive wheels **1211**, **1212** disposed at a drive end **1298** of the bot **110** and two idler wheels **1213**, **1214** disposed at a driven end **1299** of the bot **110**. The wheels **1211-1214** may be mounted to the frame **1200** in any suitable manner and be constructed of any suitable material, such as for example, low-rolling-resistance polyurethane. In alternate embodiments the bot **110** may have any suitable number of drive and idler wheels. In one exemplary embodiment, the wheels **1211-1214** may be substantially fixed relative to the longitudinal axis **1470** (FIG. 4B) of the bot **110** (e.g. the rotational plane of the wheels is fixed in a substantially parallel orientation relative to the longitudinal axis **1470** of the bot) to allow the bot **110** to move in substantially straight lines such as when, for example, the bot is travelling on a transfer deck **130B** (e.g. FIGS. 8-9B) or within a picking aisle **130A** (e.g. FIGS. 8-9B). In alternate embodiments, the rotational plane of one or more of the drive wheels and idler wheels may be pivotal (e.g. steerable) relative to the longitudinal axis **1470** of the bot for providing steering capabilities to the bot **110** by turning the rotational planes of one or more of the idler or drive wheels relative to the longitudinal axis **1470**. The wheels **1211-1214** may be substantially rigidly mounted to the frame **1200** such that the axis of rotation of each wheel is substantially stationary relative to the frame **1200**. In alternate embodiments the wheels **1211-1214** may be movably mounted to the frame by, for example, any suitable suspension device, such that the axis of rotation of the wheels **1211-1214** is movable relative to the frame **1200**. Movably mount-

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ing the wheels **1211-1214** to the frame **1200** may allow the bot **110** to substantially level itself on uneven surfaces while keeping the wheels **1211-1214** in contact with the surface.

Each of the drive wheels **1211**, **1212** may be individually driven by a respective motor **1211M**, **1212M**. The drive motors **1211M**, **1212M** may be any suitable motors such as, for exemplary purposes only, direct current electric motors. The motors **1211M**, **1212M** may be powered by any suitable power source such as by, for example, a capacitor **1400** (FIG. 4B) mounted to the frame **1200**. In alternate embodiments the power source may be any suitable power source such as, for example, a battery or fuel cell. In still other alternate embodiments the motors may be alternating current electric motors or internal combustion motors. In yet another alternate embodiment, the motors may be a single motor with dual independently operable drive trains/transmissions for independently driving each drive wheel. The drive motors **1211M**, **1212M** may be configured for bi-directional operation and may be individually operable under, for example, control of the control system **1220** for effecting steering of the bot **110** as will be described below. The motors **1211M**, **1212M** may be configured for driving the bot **110** at any suitable speed with any suitable acceleration when the bot is in either a forward orientation (e.g. drive end **1298** trailing the direction of travel) or a reverse orientation (e.g. drive end **1298** leading the direction of travel). In this exemplary embodiment, the motors **1211M**, **1212M** are configured for direct driving of their respective drive wheel **1211**, **1212**. In alternate embodiments, the motors **1211M**, **1212M** may be indirectly coupled to their respective wheels **1211**, **1212** through any suitable transmission such as, for example, a drive shaft, belts and pulleys and/or a gearbox. The drive system **1210** of the bot **110** may include an electrical braking system such as for example, a regenerative braking system (e.g. to charge, for example, a capacitor **1400** (FIG. 4B) powering the bot **110** under braking). In alternate embodiments, the bot **110** may include any suitable mechanical braking system. The drive motors may be configured to provide any suitable acceleration/deceleration rates and any suitable bot travel speeds. For exemplary purposes only the motors **1211M**, **1212M** may be configured to provide the bot (while the bot is loaded at full capacity) a rate of acceleration/deceleration of about 3.048 m/sec², a transfer deck **130B** cornering speed of about 1.524 m/sec and a transfer deck straightaway speed of about 9.144 m/sec or about 10 m/sec.

As noted above drive wheels **1211**, **1212** and idler wheels **1213**, **1214** are substantially fixed relative to the frame **1200** for guiding the bot **110** along substantially straight paths while the bot is travelling on, for example, the transfer decks **130B** (e.g. FIGS. 8-9B). Corrections in the straight line paths may be made through differential rotation of the drive wheels **1211**, **1212** as described herein. In alternate embodiments, guide rollers **1250**, **1251** may be mounted to the frame to aid in guiding the bot **110** on the transfer deck **130B** such as through contact with a wall **1801**, **2100** (FIG. 8) of the transfer deck **130B**. However, in this exemplary embodiment the fixed drive and idler wheels **1211-1214** may not provide agile steering of the bot **110** such as when, for example, the bot **110** is transitioning between the picking aisles **130A**, transfer decks **130B** or transfer areas **295** (FIGS. 8 and 11A-11E). In one exemplary embodiment, the bot **110** may be provided with one or more retractable casters **1260**, **1261** for allowing the bot **110** to make, for example, substantially right angle turns when transitioning between the picking aisles **130A**, transfer decks **130B** and bot transfer stations **140A**, **140B**. It is noted that while two casters **1260**, **1261** are shown and described, in alternate embodiments the bot **110** may have more or less

than two retractable casters. The retractable casters **1260**, **1261** may be mounted to the frame **1200** in any suitable manner such that when the casters **1260**, **1261** are in a retracted position both the idler wheels **1213**, **1214** and drive wheels **1211**, **1212** are in contact with a flooring surface such as surface **1300S** of the rails **1300** or a transfer deck **130B** of the storage structure **130**, whereas when the casters **1260**, **1261** are lowered the idler wheels **1213**, **1214** are lifted off the flooring surface. As the casters **1260**, **1261** are extended or lowered the idler wheels **1213**, **1214** are lifted off of the flooring surface so that the driven end **1299** of the bot **110** can be pivoted about a point P (FIG. **14B**) of the bot through, for example, differential rotation of the drive wheels **1211**, **1212**. For example, the motors **1211M**, **1212M** may be individually and differentially operated for causing the bot **110** to pivot about point P which is located, for example, midway between the wheels **1211**, **1212** while the driven end **1299** of the bot swings about point P accordingly via the casters **1260**, **1261**.

In other exemplary embodiments, the idler wheels **1213**, **1214** may be replaced by non-retractable casters **1260'**, **1261'** (FIG. **4C**) where the straight line motion of the bot **110** is controlled by differing rotational speeds of each of the drive wheels **1211**, **1212** as described herein. The non-retractable casters **1260'**, **1261'** may be releasably lockable casters such that the casters **1260'**, **1261'** may be selectively locked in predetermined rotational orientations to, for example, assist in guiding the bot **110** along a travel path. For example, during straight line motion of the bot **110** on the transfer deck **130B** and/or within the picking aisles **130A** the non-retractable casters **1260'**, **1261'** may be locked in an orientation such that the wheels of the casters **1260'**, **1261'** are substantially in-line with a respective one of the drive wheels **1213**, **1214** (e.g. the rotational plane of the wheels of the casters is fixed in a substantially parallel orientation relative to the longitudinal axis **1470** of the bot). The rotational plane of the wheels of non-retractable casters **1260'**, **1261'** may be locked and released relative to the longitudinal axis **1470** of the bot **110** in any suitable manner. For example, a controller **1701** (FIG. **7**) of the bot **110** may be configured to effect the locking and releasing of the casters **1260'**, **1261'** by for example controlling any suitable actuator and/or locking mechanism. In alternate embodiments any other suitable controller disposed on or remotely from the bot **110** may be configured to effect the locking and releasing of the casters **1260'**, **1261'**.

The bot **110** may also be provided with guide wheels **1250-1253**. As can be best seen in FIGS. **3B** and **3C**, while the bot **110** is travelling in, for example, the picking aisles **130A** and/or transfer areas **295** (FIGS. **8** and **11A-11E**) the movement of the bot **110** may be guided by a tracked or rail guidance system. It is noted that the transfer areas **295** may allow the bots **110** to access transport shelves **730** of the multilevel vertical conveyors **150A**, **150B**. The rail guidance system may include rails **1300** disposed on either side of the bot **110**. The rails **1300** and guide wheels **1250-1253** may allow for high-speed travel of the bot **110** without complex steering and navigation control subsystems. The rails **1300** may be configured with a recessed portion **1300R** shaped to receive the guide wheels **1250-1253** of the bot **110**. In alternate embodiments the rails may have any suitable configuration such as, for example, without recessed portion **1300R**. The rails **1300** may be integrally formed with or otherwise fixed to, for example, one or more of the horizontal and vertical supports **398**, **399** of the storage rack structure **130**. As can be seen in FIG. **3C** the picking aisles may be substantially floor-less such that bot wheel supports **1300S** of the guide rails **1300** extend away from the storage areas a predetermined distance to allow a sufficient surface area for the

wheels **1211-1214** (or in the case of lockable casters, wheels **1260'**, **1261'**) of the bot **110** to ride along the rails **1300**. In alternate embodiments the picking aisles may have any suitable floor that extends between adjacent storage areas on either side of the picking aisle. In one exemplary embodiment, the rails **1300** may include a friction member **1300F** for providing traction to the drive wheels **1211**, **1212** of the bot **110**. The friction member **1300F** may be any suitable member such as for example, a coating, an adhesive backed strip or any other suitable member that substantially creates a friction surface for interacting with the wheels of the bot **110**.

While four guide wheels **1250-1253** are shown and described it should be understood that in alternate embodiments the bot **110** may have any suitable number of guide wheels. The guide wheels **1250-1253** may be mounted to, for example, the frame **1200** of the bot in any suitable manner. In one exemplary embodiment, the guide wheels **1250-1253** may be mounted to the frame **1200**, through for example, spring and damper devices so as to provide relative movement between the guide wheels **1250-1253** and the frame **1200**. The relative movement between the guide wheels **1250-1253** and the frame may be a dampening movement configured to, for example, cushion the bot **110** and its payload against any change in direction or irregularities (e.g. misaligned joints between track segments, etc.) in the track **1300**. In alternate embodiments, the guide wheels **1250-1253** may be rigidly mounted to the frame **1200**. The fitment between the guide wheels **1250-1253** and the recessed portion **1300R** of the track **1300** may be configured to provide stability (e.g. anti-tipping) to the bot during, for example, cornering and/or extension of the transfer arm **1235** (e.g. to counteract any tipping moments created by a cantilevered load on the transfer arm). In alternate embodiments the bot may be stabilized in any suitable manner during cornering and/or extension of the transfer arm **1235**. For example, the bot **110** may include a suitable counterweight system for counteracting any moment that is created on the bot through the extension of the transfer arm **1235**.

The transfer arm **1235** may be movably mounted to the frame **1200** within, for example, the payload area **1230**. It is noted that the payload area **1230** and transfer arm **1235** may be suitably sized for transporting cases in the storage and retrieval system **100**. For example, the width W of the payload area **1230** and transfer arm **1235** may be substantially the same as or larger than a depth D (FIG. **6B**) of the storage shelves **600**. In another example, the length L of the payload area **1230** and transfer arm **1235** may be substantially the same as or larger than the largest item length transferred through the system **100** with the item length being oriented along the longitudinal axis **1470** (FIG. **4B**) of the bot **110**.

Referring also to FIGS. **4A** and **4B**, in this exemplary embodiment the transfer arm **1235** may include an array of fingers **1235A**, one or more pusher bars **1235B** and a fence **1235F**. In alternate embodiments the transfer arm may have any suitable configuration and/or components. The transfer arm **1235** may be configured to extend and retract from the payload area **1230** for transferring loads to and from the bot **110**. In one exemplary embodiment, the transfer arm **1235** may be configured to operate or extend in a unilateral manner relative to the longitudinal axis **1470** of the bot (e.g. extend from one side of the bot in direction **1471**) for increasing, for example, reliability of the bot while decreasing the bots complexity and cost. It is noted that where the transfer arm **1235** is operable only to one side of the bot **110**, the bot may be configured to orient itself for entering the picking aisles **130A** and/or transfer areas **295** with either the drive end **1298** or the driven end **1299** facing the direction of travel so that the

operable side of the bot is facing the desired location for depositing or picking a load. In alternate embodiments the bot 110 may be configured such that the transfer arm 1235 is operable or extendable in a bilateral manner relative to the longitudinal axis 1470 of the bot (e.g. extendable from both sides of the bot in directions 1471 and 1472).

In one exemplary embodiment, the fingers 1235A of the transfer arm 1235 may be configured such that the fingers 1235A are extendable and retractable individually or in one or more groups. For example, each finger may include a locking mechanism 1410 that selectively engages each finger 1235A to, for example, the frame 1200 of the bot 110 or a movable member of the transfer arm 1235 such as the pusher bar 1235B. The pusher bar 1235B (and any fingers coupled to the pusher bar), for example, may be driven by any suitable drive such as extension motor 1495. The extension motor 1495 may be connected to, for example, the pusher bar, through any suitable transmission such as, for exemplary purposes only, a belt and pulley system 1495B (FIG. 4A).

In one exemplary embodiment, the locking mechanism for coupling the fingers 1235A to, for example, the pusher bar 1235B may be, for example, a cam shaft driven by motor 1490 that is configured to cause engagement/disengagement of each finger with either the pusher bar or frame. In alternate embodiments, the locking mechanism may include individual devices, such as solenoid latches associated with corresponding ones of the fingers 1235A. It is noted that the pusher bar may include a drive for moving the pusher bar in the direction of arrows 1471, 1472 for effecting, for example, a change in orientation (e.g. alignment) of a load being carried by the bot 110, gripping a load being carried by the bot 110 or for any other suitable purpose. In one exemplary embodiment, when one or more locking mechanisms 1410 are engaged with, for example, the pusher bar 1235B the respective fingers 1235A extend and retract in the direction of arrows 1471, 1472 substantially in unison with movement of the pusher bar 1235B while the fingers 1235A whose locking mechanisms 1410 are engaged with, for example, the frame 1200 remain substantially stationary relative to the frame 1200.

In another exemplary embodiment, the transfer arm 1235 may include a drive bar 1235D or other suitable drive member. The drive bar 1235D may be configured so that it does not directly contact a load carried on the bot 110. The drive bar 1235D may be driven by a suitable drive so that the drive bar 1235D travels in the direction of arrows 1471, 1472 in a manner substantially similar to that described above with respect to the pusher bar 1235B. In this exemplary embodiment, the locking mechanisms 1410 may be configured to latch on to the drive bar 1235D so that the respective fingers 1235A may be extended and retracted independent of the pusher bar and vice versa. In alternate embodiments the pusher bar 1235B may include a locking mechanism substantially similar to locking mechanism 1410 for selectively locking the pusher bar to either the drive bar 1235D or the frame 1200 where the drive bar is configured to cause movement of the pusher bar 1235B when the pusher bar 1235B is engaged with the drive bar 1235D.

In one exemplary embodiment, the pusher bar 1235B may be a one-piece bar that spans across all of the fingers 1235A. In other exemplary embodiments, the pusher bar 1235B may be a segmented bar having any suitable number of segments 1235B1, 1235B2. Each segment 1235B1, 1235B2 may correspond to the groups of one or more fingers 1235A such that only the portion of the pusher bar 1235B corresponding to the finger(s) 1235A that are to be extended/retracted is moved in the direction of arrows 1471, 1472 while the remaining seg-

ments of the pusher bar 1235B remain stationary so as to avoid movement of a load located on the stationary fingers 1235A.

The fingers 1235A of the transfer arm 1235 may be spaced apart from each other by a predetermined distance so that the fingers 1235A are configured to pass through or between corresponding support legs 620L1, 620L2 of the storage shelves 600 (FIG. 5A) and corresponding support fingers 910 of the shelves 730 on the multilevel vertical conveyors 150A, 150B. In alternate embodiments the fingers 1235A may be configured to pass through corresponding support fingers of bot transfer stations for passing the bot load to multilevel vertical conveyor through the bot transfer station. The spacing between the fingers 1235A and a length of the fingers of the transfer arm 1235 allows an entire length and width of the loads being transferred to and from the bot 110 to be supported by the transfer arm 1235.

The transfer arm 1235 may include any suitable lifting device(s) 1235L configured to move the transfer arm 1235 in a direction 1350 (FIG. 13B) substantially perpendicular to a plane of extension/retraction of the transfer arm 1235.

Referring also to FIGS. 5A-5C, in one example, a load (substantially similar to loads 750-753) is acquired from, for example, a storage shelf 600 by extending the fingers 1235A of the transfer arm 1235 into the spaces 620S between support legs 620L1, 620L2 of the storage shelf 600 and under one or more target items 1500 located on the shelf 600. The transfer arm lift device 1235L is suitably configured to lift the transfer arm 1235 for lifting the one or more target items 1500 off of the shelf 600. The fingers 1235A are retracted so that the one or more target items are disposed over the payload area 1230 of the bot 110. The lift device 1235L lowers the transfer arm 1235 so the one or more target items are lowered into the payload area 1230 of the bot 110. In alternate embodiments, the storage shelves 600 may be configured with a lift motor for raising and lowering the target items where the transfer arm 1235 of the bot 110 does not include a lift device 1235L. FIG. 5B illustrates an extension of three of the fingers 1235A for transferring a load 1501. FIG. 5C shows a shelf 1550 having two items or loads 1502, 1503 located side by side. In FIG. 5C, three fingers 1235A of the transfer arm 1235 are extended for acquiring only load 1502 from the shelf 1550. As can be seen in FIG. 5C, it is noted that the loads carried by the bots 110 may include cases of individual items (e.g. load 1502 includes two separate boxes and load 1503 includes three separate boxes). It is also noted that in one exemplary embodiment the extension of the transfer arm 1235 may be controlled for retrieving a predetermined number of items from an array of items. For example, the fingers 1235A in FIG. 5C may be extended so that only item 1502A is retrieved while item 1502B remains on the shelf 1550. In another example, the fingers 1235A may be extended only part way into a shelf 600 (e.g. an amount less than the depth D of the shelf 600) so that a first item located at, for example, the front of the shelf (e.g. adjacent the picking aisle) is picked while a second item located at the back of the shelf, behind the first item, remains on the shelf.

As noted above the bot 110 may include a retractable fence 1235F. Referring to FIGS. 6A-6D, the fence 1235F may be movably mounted to the frame 1200 of the bot 110 in any suitable manner so that the loads, such as load 1600, pass over the retracted fence 1235F as the loads are transferred to and from the bot payload area 1230 as can be seen in FIG. 6A. Once the load 1600 is located in the payload area 1230, the fence 1235F may be raised or extended by any suitable drive motor 1610 so that the fence 1235F extends above the fingers 1235A of the bot 110 for substantially preventing the load

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1600 from moving out of the payload area 1230 as can be seen in FIG. 6B. The bot 110 may be configured to grip the load 1600 to, for example, secure the load during transport. For example, the pusher bar 1235B may move in the direction of arrow 1620 towards the fence 1235F such that the load 1600 is sandwiched or gripped between the pusher bar 1235B and the fence 1235F as can be seen in FIGS. 6C and 6D. As may be realized, the bot 110 may include suitable sensors for detecting a pressure exerted on the load 1600 by the pusher bar 1235B and/or fence 1235F so as to prevent damaging the load 1600. In alternate embodiments, the load 1600 may be gripped by the bot 110 in any suitable manner.

Referring again to FIGS. 4B and 4C, the bot 110 may include a roller bed 1235RB disposed in the payload area 1230. The roller bed 1235RB may include one or more rollers 1235R disposed transversely to the longitudinal axis 1470 of the bot 110. The rollers 1235R may be disposed within the payload area 1230 such that the rollers 1235R and the fingers 1235A are alternately located so that the fingers 1235A may pass between the rollers 1235R for transferring items to and from the payload area 1230 as described above. One or more pushers 1235P may be disposed in the payload area 1230 such that a contact member of the one or more pushers 1235P extends and retracts in a direction substantially perpendicular to the axis of rotation of the rollers 1235R. The one or more pushers 1235P may be configured to push the load 1600 back and forth within the payload area 1230 in the direction of arrow 1266 (e.g. substantially parallel to the longitudinal axis 1470 of the bot 110) along the rollers 1235R for adjusting a position of the load 1600 longitudinally within the payload area 1230. In alternate embodiments, the rollers 1235R may be driven rollers such that a controller of, for example, the bot drives the rollers for moving the load 1600 such that the load is positioned at a predetermined location within the payload area 1230. In still other alternate embodiments the load may be moved to the predetermined location within the payload area in any suitable manner. The longitudinal adjustment of the load 1600 within the payload area 1230 may allow for positioning of the loads 1600 for transferring the loads from the payload area to, for example, a storage location or other suitable location such as the multilevel vertical conveyors 150A, 150B or bot transfer stations 140A, 140B.

Referring now to FIG. 7, the control system 1220 of the bot will be described. The control system 1220 may be configured to provide communications, supervisory control, bot localization, bot navigation and motion control, case sensing, case transfer and bot power management. In alternate embodiments the control system 1220 may be configured to provide any suitable services to the bot 110. The control system 1220 may include any suitable programs or firmware configured for performing the bot operations described herein. The control system 1220 may be configured to allow for remote (e.g. over a network) debugging of the bot. In one example, the firmware of the bot may support a firmware version number that can be communicated over, for example, the network 180 so the firmware may be suitably updated. The control system 1220 may allow for assigning a unique bot identification number to a respective bot 110 where the identification number is communicated over the network 180 (FIG. 1) to, for example, track a status, position or any other suitable information pertaining to the bot 110. In one example, the bot identification number may be stored in a location of the control system 1220 such that the bot identification number is persistent across a power failure but is also changeable.

In one exemplary embodiment, the control system 1220 may be divided into a front end 1220F (FIG. 2) and back end

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1220B (FIG. 2) having any suitable subsystems 1702, 1705. The control system 1220 may include an on-board computer 1701 having, for example, a processor, volatile and non-volatile memory, communication ports and hardware interface ports for communicating with the on-board control subsystems 1702, 1705. The subsystems may include a motion control subsystem 1705 and an input/output subsystem 1702. In alternate embodiments, the bot control system 1220 may include any suitable number of portions/subsystems.

The front end 1220F may be configured for any suitable communications (e.g. synchronous or asynchronous communications regarding bot commands, status reports, etc.) with the control server 120. The communications between the bot 110 and the control server 120 may, in one exemplary embodiment, provide for a substantially automatic bootstrap from, for example, initial installation of the bot 110, operational failure of the bot 110 and/or bot replacement. For example, when a bot 110 is initialized, the bot may obtain an identification number and subscribe to a bot proxy 2680 (FIG. 26A) via communication with the front end 1220F. This allows the bot to become available for receiving tasks. The front end 1220F may receive and decompose tasks assigned to the bot 110 and reduce the task into primitives (e.g. individual commands) that the back end 1220B can understand. In one example, the front end 1220F may consult any suitable resources such as, for example, a map of the storage structure 130 (FIG. 1) to decompose a task into the primitives and to determine the various movement related parameters (e.g. velocity, acceleration, deceleration, etc.) for each portion of the task. The front end 1220F may pass the primitives and movement related parameters to the back end 1220B for execution by the bot 110. The bot front end 1220F may be configured as a pair of state machines where a first one of the state machines handles communication between the front end 1220F and the control server 120 and a second one of the state machines handles communication between the front end 1220F and the back end 1220B. In alternate embodiments the front end 1220F may have any suitable configuration. The first and second state machines may interact with each other by generating events for each other. The state machines may include a timer for handling timeouts such as during, transfer deck 130B access. In one example, when a bot 110 is entering a transfer deck 130B (e.g. FIG. 8), a bot proxy of the central system control computers may inform the front end 1220F of a predetermined entrance time that the bot is to enter the transfer deck 130B. The front end 1220F may start the timer of the state machines according to a time the bot is to wait (based on the predetermined entrance time) before entering the deck. It is noted that the timers (e.g. clocks) of the state machines and the bot proxy 2680 may be synchronized clocks so as to substantially avoid collisions between bots travelling on the transfer deck 130B and bots entering the transfer deck 130B.

The back end 1220B may be configured to effect the functions of the bot described above (e.g. lowering the casters, extending the fingers, driving the motors, etc.) based on, for example, the primitives received from the front end 1220F. In one example, the back end 1220B may monitor and update bot parameters including, but not limited to, bot position and velocity and send those parameters to the bot front end 1220F. The front end 1220F may use the parameters (and/or any other suitable information) to track the bot's 110 movements and determine the progress of the bot task(s). The front end 1220F may send updates to, for example, the bot proxy 2680 so that the control server 120 can track the bot movements and task progress and/or any other suitable bot activities.

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The motion control subsystem **1705** may be part of the back end **1220B** and configured to effect operation of, for example, the drive motors **1211M**, **1212M**, **1235L**, **1495**, **1490**, **1610** of the bot **110** as described herein. The motion control subsystem **1705** may be operatively connected to the computer **1701** for receiving control instructions for the operation of, for example, servo drives (or any other suitable motor controller) resident in the motion control subsystem **1705** and subsequently their respective drive motors **1211M**, **1212M**, **1235L**, **1495**, **1490**, **1610**. The motion control subsystem **1705** may also include suitable feedback devices, such as for example, encoders, for gathering information pertaining to the drive motor operation for monitoring, for example, movement the transfer arm **1235** and its components (e.g. when the fingers **1235A** are latched to the pusher bar, a location of the pusher bar, extension of the fence, etc.) or the bot **110** itself. For example, an encoder for the drive motors **1211M**, **1212M** may provide wheel odometry information, and encoders for lift motor **1235L** and extension motor **1495** may provide information pertaining to a height of the transfer arm **1235** and a distance of extension of the fingers **1235A**. The motion control subsystem **1705** may be configured to communicate the drive motor information to the computer **1701** for any suitable purpose including but not limited to adjusting a power level provided to a motor.

The input/output subsystem **1702** may also be part of the back end **1220B** and configured to provide an interface between the computer **1701** and one or more sensors **1710-1716** of the bot **110**. The sensors may be configured to provide the bot with, for example, awareness of its environment and external objects, as well as the monitor and control of internal subsystems. For example, the sensors may provide guidance information, payload information or any other suitable information for use in operation of the bot **110**. For exemplary purposes only, the sensors may include a bar code scanner **1710**, slat sensors **1711**, line sensors **1712**, case overhang sensors **1713**, arm proximity sensors **1714**, laser sensors **1715** and ultrasonic sensors **1716**.

The bar code scanner(s) **1710** may be mounted on the bot **110** in any suitable location. The bar code scanners(s) **1710** may be configured to provide an absolute location of the bot **110** within the storage structure **130**. The bar code scanner(s) **1710** may be configured to verify aisle references and locations on the transfer decks by, for example, reading bar codes located on, for example the transfer decks, picking aisles and transfer station floors to verify a location of the bot **110**. The bar code scanner(s) **1710** may also be configured to read bar codes located on items stored in the shelves **600**.

The slat sensors **1711** may be mounted to the bot **110** at any suitable location. The slat sensors **1711** may be configured to count the slats or legs **620L1**, **620L2** of the storage shelves **600** (e.g. FIG. 5A) for determining a location of the bot **110** with respect to the shelving of, for example, the picking aisles **130A**. The slat information may be used by the computer **1701** to, for example, correct the bot's odometry and allow the bot **110** to stop with its fingers **1235A** positioned for insertion into the spaces between the legs **620L1**, **620L2**. In one exemplary embodiment, the bot may include slat sensors **1711** on the drive end **1298** and the driven end **1299** of the bot to allow for slat counting regardless of which end of the bot is facing the direction the bot is travelling. The slat sensors **1711** may be any suitable sensors such as, for example, close range triangulation or "background suppression" sensors. The slat sensors **1711** may be oriented on the bot **110** so that the sensors see down into the slats and ignore, for example, the thin edges of the legs **620L1**, **620L2**. For exemplary purposes only, in one exemplary embodiment the slat sensors **1711** may

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be mounted at about a 15 degree angle from perpendicular (relative to the longitudinal axis **1470** (FIG. 4B) of the bot **110**). In alternate embodiments the slat sensors **1711** may be mounted on the bot in any suitable manner.

The line sensors **1712** may be any suitable sensors mounted to the bot in any suitable location, such as for exemplary purposes only, on bumpers **1273** (FIG. 2) disposed on the drive and driven ends of the bot **110**. For exemplary purposes only, the line sensors may be diffuse infrared sensors. The line sensors **1712** may be configured to detect guidance lines provided on, for example, the floor of the transfer decks **130B** (e.g. FIG. 8). The bot **110** may be configured to follow the guidance lines when travelling on the transfer decks **130B** and defining ends of turns when the bot is transitioning on or off the transfer decks **130B**. The line sensors **1712** may also allow the bot **110** to detect index references for determining absolute localization where the index references are generated by crossed guidance lines. In this exemplary embodiment the bot **110** may have about six line sensors **1712** but in alternate embodiments the bot **110** may have any suitable number of line sensors.

The case overhang sensors **1713** may be any suitable sensors that are positioned on the bot to span the payload area **1230** adjacent the top surface of the fingers **1235A**. The case overhang sensors **1713** may be disposed at the edge of the payload area **1230** to detect any loads that are at least partially extending outside of the payload area **1230**. In one exemplary embodiment, the case overhang sensors **1713** may provide a signal to the computer **1701** (when there is no load or other items obstructing the sensor) indicating that the fence **1235F** may be raised for securing the load(s) within the payload area **1230**. In other exemplary embodiments, the case overhang sensors **1713** may also confirm a retraction of the fence **1235F** before, for example, the fingers **1235A** are extended and/or a height of the transfer arm **1235** is changed.

The arm proximity sensors **1714** may be mounted to the bot **110** in any suitable location, such as for example, on the transfer arm **1235**. The arm proximity sensors **1714** may be configured to sense objects around the transfer arm **1235** and/or fingers **1235A** of the transfer arm **1235** as the transfer arm **1235** is raised/lowered and/or as the fingers **1235A** are extended/retracted. Sensing objects around the transfer arm **1235** may, for exemplary purposes only, substantially prevent collisions between the transfer arm **1235** and objects located on, for example, shelves **600** (e.g. FIG. 5A) or the horizontal and/or vertical supports of the storage structure **130**.

The laser sensors **1715** and ultrasonic sensors **1716** (collectively referred to as case sensors) may be configured to allow the bot **110** to locate itself relative to each case unit forming the load carried by the bot **110** before the case units are picked from, for example, the storage shelves **600** and/or multilevel vertical conveyor (or any other location suitable for retrieving payload). The case sensors may also allow the bot to locate itself relative to empty storage locations for placing case units in those empty storage locations. This location of the bot relative to the case units to be picked and/or empty storage locations for placing the case units may be referred to as bot localization, which will be described in greater detail below. The case sensors may also allow the bot **110** to confirm that a storage slot (or other load depositing location) is empty before the payload carried by the bot is deposited in, for example, the storage slot. In one example, the laser sensor **1715** may be mounted to the bot at a suitable location for detecting edges of items to be transferred to (or from) the bot **110**. The laser sensor **1715** may work in conjunction with, for example, retro-reflective tape (or other suitable reflective surface, coating or material) located at, for example, the back of

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the shelves **600** to enable the sensor to “see” all the way to the back of the storage shelves **600**. The reflective tape located at the back of the storage shelves allows the laser sensor **1715** to be substantially unaffected by the color, reflectiveness, roundness or other suitable characteristics of the items located on the shelves **600**. The ultrasonic sensor **1716** may be configured to measure a distance from the bot **110** to the first item in a predetermined storage area of the shelves **600** to allow the bot **110** to determine the picking depth (e.g. the distance the fingers **1235A** travel into the shelves **600** for picking the item(s) off of the shelves **600**). One or more of the case sensors may allow for detection of case orientation (e.g. skewing of cases within the storage shelves **600**) by, for example, measuring the distance between the bot **110** and a front surface of the case units to be picked as the bot **110** comes to a stop adjacent the case units to be picked. The case sensors may allow verification of placement of a case unit on, for example, a storage shelf **600** by, for example, scanning the case unit after it is placed on the shelf.

It is noted that the computer **1701** and its subsystems **1702**, **1705** may be connected to a power bus for obtaining power from, for example, the capacitor **1400** through any suitable power supply controller **1706**. It is noted that the computer **1701** may be configured to monitor the voltage of the capacitor **1400** to determine its state of charge (e.g. its energy content). In one exemplary embodiment, the capacitor may be charged through charging stations located at, for example, one or more transfer areas **295** (FIGS. **8** and **11A-11E**) or at any other suitable location of the storage structure **130** so that the bot is recharged when transferring payloads and remains in substantially continuous use. The charging stations may be configured to charge the capacitor **1400** within the time it takes to transfer the payload of the bot **110**. For exemplary purposes only, charging of the capacitor **1400** may take about 15 seconds. In alternate embodiments, charging the capacitor may take more or less than about 15 seconds. During charging of the capacitor **1400** the voltage measurement may be used by the computer **1701** to determine when the capacitor is full and to terminate the charging process. The computer **1701** may be configured to monitor a temperature of the capacitor **1400** for detecting fault conditions of the capacitor **1400**.

The computer **1701** may also be connected to a safety module **1707** which includes, for example, an emergency stop device **1311** (FIG. **3A**) which when activated effects a disconnection of power to, for example, the motion control subsystem **1705** (or any other suitable subsystem(s) of the bot) for immobilizing or otherwise disabling the bot **110**. It is noted that the computer **1701** may remain powered during and after activation of the emergency stop device **1311**. The safety module **1707** may also be configured to monitor the servo drives of the motion control subsystem **1705** such that when a loss of communication between the computer and one or more of the servo drives is detected, the safety module **1707** causes the bot to be immobilized in any suitable manner. For example, upon detection of a loss of communication between the computer **1701** and one or more servo drives the safety module **1707** may set the velocity of the drive motors **1211M**, **1212M** to zero for stopping movement of the bot **110**.

The communication ports of the control system **1220** may be configured for any suitable communications devices such as, for example, a wireless radio frequency communication device **1703** (including one or more antennae **1310**) and any suitable optical communication device **1704** such as, for example, an infrared communication device. The wireless radio frequency communication device **1703** may be configured to allow communication between the bot **110** and, for example, the control server **120** and/or other different bots

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110 over any suitable wireless protocol. For exemplary purposes only, the wireless protocol for communicating with the control server **120** may be the wireless 802.11 network protocol (or any other suitable wireless protocol). Communications within the bot control system **1220** may be through any suitable communication bus such as, for example, a control network area bus. It is noted that the control server **120** and the bot control system **1220** may be configured to anticipate momentary network communication disruptions. For example, the bot may be configured to maintain operation as long as, for example, the bot **110** can communicate with the control server **120** when the bot **110** transits a predetermined track segment and/or other suitable way point. The optical communication device **1704** may be configured to communicate with, for example, the bot transfer stations for allowing initiation and termination of charging the capacitor **1400**. The bot **110** may be configured to communicate with other bots **110** in the storage and retrieval system **100** to form a peer-to-peer collision avoidance system so that bots can travel throughout the storage and retrieval system **100** at predetermined distances from each other in a manner substantially similar to that described in U.S. patent application Ser. No. 12/757,337, entitled “CONTROL SYSTEM FOR STORAGE AND RETRIEVAL SYSTEMS,” previously incorporated by reference herein in its entirety.

Referring to FIGS. **2**, **4B** and **8-13B**, bot navigation and motion control will be described. Generally, in accordance with the exemplary embodiments, the bot **110** has, for example, three modes of travel. In alternate embodiments the bot **110** may have more than three modes of travel. For exemplary purposes only, in the picking aisles **130A** the bot travels on wheels **1211-1214** (or lockable casters **1260'**, **1261'** in lieu of idler wheels **1213**, **1214**) and is guided by guide wheels **1250-1253** against the sides of track **1300** (FIG. **3B**). On the transfer deck **130B**, the bot **110** uses casters **1261**, **1262** (or releases lockable casters **1260'**, **1261'**) while making substantially right angle turns when transitioning from/to the picking aisles **130A** or transfer stations **140A**, **140B**. For traveling long distances on, for example, the transfer deck **130B** the bot **110** travels on wheels **1211-1214** (or lockable casters **1260'**, **1261'** in lieu of idler wheels **1213**, **1214** where the casters **1260'**, **1261'** are rotationally locked as described above) using a “skid steering” algorithm (e.g. slowing down or stopping rotation of one drive wheel relative to the other drive wheel to induce a turning motion on the bot) to follow guidance lines **1813-1817** on the transfer deck **130B**.

When traveling in the picking aisles **130A**, the bot **110** travels in substantially straight lines. These substantially straight line moves within the picking aisles **130A** can be in either direction **1860**, **1861** and with either bot orientation (e.g. a forward orientation with the drive end **1298** trailing the direction of travel and a reverse orientation with the drive end **1298** leading the direction of travel). During straight line motion on the transfer deck **130B** the bot **110** travels in, for exemplary purposes only, a counterclockwise direction **1863**, with a forward bot orientation. In alternate embodiments the bot may travel in any suitable direction with any suitable bot orientation. In still other alternate embodiments, there may be multiple travel lanes allowing bots to travel in multiple directions (e.g. one travel lane has a clockwise direction of travel and another travel lane has a counter-clockwise direction of travel). In one example, the turns to and from the picking aisles **130A** and/or transfer areas **295** are about 90 degrees where the center point of rotation **P** of the bot is located substantially midway between the drive wheels **1211**, **1212** such that the bot can rotate clockwise or counterclockwise. In alternate embodiments the bot turns may be more or less than

about 90 degrees. In another example, the bot may make a substantially 180 degree turn (i.e. two substantially 90 degree turns made in sequence without a stop) as will be described below.

As described above, the transfer deck **130B** may include guidance lines **1810-1817** for guiding the bot **110**. The guidance lines **1810-1817** may be any suitable lines adhered to, formed in or otherwise affixed to the transfer deck **130B**. For exemplary purposes only, in one example the guidance lines may be a tape affixed to the surface of the transfer deck **130B**. In this exemplary embodiment the transfer deck **130B** includes a track **1800** having a first side **1800A** and a second side **1800B** separated by a wall **1801**. The first and second sides **1800A**, **1800B** of the track **1800** are joined by end track sections **1800E** (only one of which is shown in FIG. **8**). In alternate embodiments the track **1800** may have any suitable configuration. Each of the first and second sides **1800A**, **1800B** includes two travel lanes defined by, for example, guidance lines **1813**, **1814** and **1816**, **1817** respectively. The end track portions **1800E** include, for example, one travel lane defined by, for example, guidance line **1815**. In alternate embodiments the sections/sides of the track **1800** may have any suitable number of travel lanes defined in any suitable manner. In accordance with the exemplary embodiments each picking lane **130A** and/or transfer area **295**, includes a lead in/out guidance line **1810-1812**. The lead in/out guidance lines **1810-1812** and the single guidance line **1815** of the end track portions **1800E** may be detected by the bot **110** as index marks for bot localization during long line-following moves. The lead in/out guidance lines **1810-1812** and guidance line **1815** may also be detected by the bot **110** as reference marks for making turns.

When the bot **110** moves in substantially straight lines, such as in the picking aisles **130A** and/or transfer areas **295**, the drives for motors **1211M**, **1212M** may be configured as torque controllers. For example, the computer **1701** may be configured to close a velocity loop as shown in FIG. **10** using the average of the velocity feedback from both wheels **1211**, **1212** as the "bot velocity". To improve performance and avoid velocity loop instabilities, the velocity loop may be augmented with torque-feedforward and operated at a low gain. The computer **1701** may also be configured to close a position loop as also shown in FIG. **10** for final position at a stop location of the bot **110**. The computer **1701** may also be configured to sum in a differential torque offset to implement line following. It is noted that the drive wheels **1211**, **1212** may lose traction with the transfer deck **130A** or floor of a picking aisle **130A** or transfer area **295** when the flooring surfaces and/or the wheels are contaminated with liquids, dirt or other particulates. The velocity control loop may be configured to mitigate the loss of traction by backing off the torque to both wheels **1211**, **1212** whenever feedback provided by, for example, an encoder for one or both wheels **1211**, **1212** indicates a velocity higher than a predetermined velocity of the bot **110**.

When travelling long distances on, for example, the transfer deck, the bot **110** travels on drive wheels **1211**, **1212** and idler wheels **1213**, **1214** (or locked casters **1260'**, **1261'**) so that the bot is deterred from veering off of the straight line trajectory through the fixed nature of the drive wheels **1211**, **1212** and idler wheels **1213**, **1214** (or locked casters **1260'**, **1261'**). The computer **1701** may be configured with any suitable line following algorithm to substantially ensure that the bot **110** maintains travel in a straight line. The line following algorithm may also allow for correction of initial line following errors due to, for example, misalignment from turns. In one exemplary embodiment the bot **110** uses line sensors

1712 to estimate its heading and offset from a guidance line **1810-1817**. The bot **110** may be configured to use, for example, any suitable algorithm such as a fuzzy logic algorithm to generate corrections in the travel path of the bot **110**. The correction may be applied as a differential torque to the wheels as the bot is travelling (e.g. skid steering—rotating one drive wheel slower than the other drive wheel to produce increased drag on one side of the bot for inducing a turning moment on the bot).

For turns, such as for example, substantially right angle turns, the drives for motors **1211M**, **1212M** may be configured as position controllers. For example the drives may be commanded by the computer **1701** to rotate their respective wheels in opposite directions for a predetermined distance to generate a pivot turn of slightly more than about 90 degrees. When for example, line sensors **1712** detect a stopping guidance line, the turning move is terminated. In alternate embodiments the drives for the motors **1211M**, **1212M** may be operated in any suitable manner for driving the bot in substantially straight lines or during turns.

FIGS. **9A** and **9B** illustrate an exemplary turn sequence for a substantially 90 degree turn made by the bot **110** while transitioning onto the transfer deck **130B** from a picking aisle **130A**. In this example, the bot is traveling in a forward orientation in the direction of arrow **1910**. As the bot **110** exits the picking aisle **130A**, the bot **110** lowers the casters **1260**, **1261** (FIG. **4A**) so that the idler wheels **1213**, **1214** are lifted off of the transfer deck **130B** (or unlocks casters **1260'**, **1261'**). Using line sensors **1712** located at for example the driven end **1299** of the bot **110**, the bot **110** detects the inner travel lane guidance line **1814** and then using corrected wheel odometry, stops with its pivot point P at or close to the outer travel lane guidance line **1813**. The bot **110** rotates about 90 degrees in the direction of arrow **1920** using a differential torque in the drive motors **1211M**, **1212M** to turn the drive wheels **1211**, **1212** in opposite directions such that the bot **110** rotates about point P. The bot **110** detects the guidance line **1813** with the line sensors **1712** and terminates the turn. The bot **110** raises the casters **1260**, **1260** so that the idler wheels **1213**, **1214** contact the transfer deck **130B** (or locks casters **1260'**, **1261'**) and proceeds to follow guidance line **1813** using, for example, line following. It is noted that turning of the bot to enter, for example, picking aisle **130A** may occur in substantially the same manner as that described above for exiting the picking aisle **130A**.

FIGS. **11A-13B** illustrate exemplary travel paths of a bot **110** including straight line travel and turn sequences. It is noted that while the specific examples of bot travel are shown and described, the bot **110** may be configured to perform any suitable number of turns and transition between any suitable number of travel lanes in any suitable manner for travelling throughout a respective level of the storage structure **130**. FIG. **11A** illustrates a travel path of the bot **110** where the bot **110** transitions from one, for example, picking aisle (or transfer station), across the transfer deck **130B** and into a transfer area **295** (or other picking aisle) with the bot **110** transitioning from a reverse orientation (e.g. drive end **1298** leading) to a forward orientation (e.g. drive end **1298** trailing). In this example, the bot **110** exits the picking aisle **130A** in a reverse orientation such that a line sensor(s) **1712** disposed substantially at pivot point P detects the inner travel lane guidance line **1814**. The bot **110** pivots about point P in a counterclockwise direction in a manner substantially similar to that described above with respect to FIGS. **9A** and **9B**. The bot follows guidance line **1814** in a forward orientation until, for example, line sensors **1712** (located proximately to or at one or more of the drive end **1298** and driven end **1299** of the bot

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110) detect the crossing of guidance lines **1814** and **1815** (FIG. **8**) at which point the bot **110** pivots counterclockwise about point P in a manner similar to that described above so that the bot follows line **1815** substantially to a point where guidance line **1815** crosses the inner travel lane guidance line **1816**. At the crossing of guidance lines **1815**, **1816** the bot **110** pivots counterclockwise to follow guidance line **1816**. The bot follows guidance line **1816** until the line sensors **1712** detect a crossing of guidance lines **1816** and **1812** at which point the bot pivots clockwise to enter transfer area **295** in a forward orientation.

FIG. **11B** illustrates an exemplary travel path of the bot **110** where the bot exits the picking aisle **130A** in a reverse orientation and enters transfer area **295** in a reverse orientation. In this example, the motion of the bot is substantially similar to that described above with respect to FIG. **11A**, however, after travelling around wall **1801** the bot transitions to the outer travel lane guidance line **1817** so that the bot **110** is in a reverse orientation. The reverse orientation of the bot **110** allows the bot to pivot counterclockwise into an open area of the transfer deck **130B** for entering the transfer area **295** in a forward orientation without colliding with the outside wall **2100** of the transfer deck **130B**.

FIG. **11C** illustrates the bot **110** exiting the picking aisle **130A** in a forward orientation and entering transfer area **295** in a forward orientation. The motion of the bot is substantially similar to that described above however, in this example, the bot **110** transitions from outer travel lane guidance line **1813** to inner travel lane guidance line **1816** so that the bot can enter the transfer area **295** in a forward orientation.

FIGS. **11D** and **11E** illustrate the bot **110** exiting the picking aisle **130A** in a forward orientation and entering the transfer area **295** in a reverse orientation using the outer travel lane guidance lines **1813** and **1817**. The motion of the bot **110** may be substantially similar to that described above, however as the bot **110** travels along guidance line **1815** the bot **110** makes three turns **2110-2112** (e.g. where turns **2110**, **2111** turn the bot substantially 180 degrees along guidance line **1815**) to orient the bot **110** for making the final turn **2113** into the transfer area **295**. As can be seen in FIG. **11E**, without the additional turn the bot **110** would not be able to transition from outer travel lane guidance line **1813** onto outer travel lane guidance line **1817** without colliding with the outer wall **2100** (as indicated by the shaded area) using line following as described herein.

FIGS. **12A** and **12B** illustrate an exemplary travel path of bot **110** from picking aisle **130A1** to picking aisle **130A2** where travel of the bot **110** within the picking aisle **130A1** is in a forward orientation and travel within picking aisle **130A2** is in a reverse orientation. In this example, the bot uses the outer travel lane guidance line **1813** for transitioning between picking aisles **130A1**, **130A2**. As can be seen in FIG. **12A** when travelling along the outer travel lane guidance line **1813** and entering picking aisle **130A2** the bot pivots in a direction so the driven end **1299** of the bot swings towards the inner travel lane of the transfer deck **130B** so as to avoid colliding with the outer wall **2100** as shown in FIG. **12B**.

FIGS. **13A** and **13B** illustrate an exemplary travel path of bot **110** from picking aisle **130A1** to picking aisle **130A2** where travel of the bot **110** within the picking aisles **130A1**, **130A2** is in a reverse orientation. In this example, the bot uses the inner travel lane guidance line **1814** for transitioning between picking aisles **130A1**, **130A2**. As can be seen in FIG. **13A** when travelling along the inner travel lane guidance line **1814** the bot pivots in a direction so the driven end **1299** of the

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bot swings towards the outer travel lane of the transfer deck **130B** so as to avoid colliding with the inner wall **1801** as shown in FIG. **13B**.

It is noted that the bot may be configured to transition between the tracked travel lanes of the picking aisles **130A** and the open transfer deck **130B** in any suitable manner. In one exemplary embodiment, the guidance lines **1810-1812** may guide the bot into the tracks **1300** of the picking aisles. In alternate embodiments, one or more of the sensors **1710-1716** may allow the bot **110** to detect, for example, edges or other suitable features of the tracks **1300** (FIG. **3B**) and position itself so the bot **110** passes between opposing tracks **1300** with the guide wheels contacting the recesses **1300R** in the tracks **1300**.

In accordance with one exemplary embodiment, in the above described examples of the bot travel paths, when the bot is turning the bot is supported by the drive wheels **1211**, **1212** and the casters **1260**, **1261** (or casters **1260'**, **1261'**). The straight line moves of the bot may be made with the bot supported on the drive wheels **1211**, **1212** and the idler wheels **1213**, **1214** (or casters **1260'**, **1261'**). As noted above, any corrections to the bot travel path while the bot is traveling in a straight line may be made using skid steering. In alternate embodiments, the bot may travel in a straight line path with the casters **1260**, **1261** deployed. In still other alternate embodiments, correction to the bots straight line travel paths may be made through steerable wheels.

Referring again to FIG. **7**, the bot **110** can determine its position within the storage and retrieval system **100** for transitioning through the storage structure **130** as described above through, for example, bot localization. In one exemplary embodiment bot localization may be derived through one or more of bot odometry, slat counting, index counting and bar code reading. As described above, the bot odometry may be provided from encoders associated with, for example, wheels **1211-1214** (FIG. **2**). It is noted that encoder information from each wheel **1211-1214** may be averaged and scaled in any suitable manner to provide a distance traveled by the bot. In alternate embodiments, the distance traveled by the bot may be obtained from the wheel encoder information in any suitable manner. The slat counting may be provided by, for example, the slat sensors **1711** as the bot travels through the picking aisles. The slat counting may supplement the odometry information when the bot is within the picking aisles. The index counting may be provided, by for example, the line sensors **1712** as the bot passes over crossed sections of the guidance lines **1810-1817** (FIG. **8**). The index counting may supplement the bot odometry when the bot is traveling on the transfer deck **130B**. Bar code reading may be provided by bar code scanner **1710**. The bar code reading may be configured to allow the bot **110** to determine an initial position of the bot such as when the bot is powered up from an off or dormant state. The bar codes may be located at transfer stations **140A**, **140B** (FIG. **1**) or any other suitable location within the storage structure **130** for initializing the bot **110**. Bar codes may also be located within the picking aisles and on the transfer deck to, for example, confirm bot location and correct for missed slats or indexes. The on-board computer **1701** of the bot **110** may be configured to use any suitable combination of bot odometry, slat counting, index counting and bar code reading to determine the bot's **110** position within the storage structure **130**. In alternate embodiments, the computer **1701** may be configured to determine the location of the bot using only one or any suitable combination of bot odometry, slat counting, index counting and bar code reading. In still other alternate embodiments, the location of the bot may be determined in any suitable manner such as through, for example,

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an indoor spatial positioning system. The indoor spatial positioning system may be substantially similar to a global positioning system and use any suitable technique for determining the position of an object such as, for example, acoustic, optical, or radio frequency signaling.

In one exemplary embodiment, one or more of the sensors **1710-1716** described above may allow for dynamic positioning of bots **110** within the picking aisles **130A** in any suitable manner. The position at which the bot **110** is stopped for dynamically allocating case units may be determined by, for example, the control server **120** (FIG. 1), the control system **1220** of the bot or by a combination thereof. For example, dynamic allocation of the storage space may be determined by, for example, the control server **120** in any suitable manner such that any open storage spaces in the storage structure **130** are filled with items having a size capable of fitting within those open storage spaces. The control server may communicate to the appropriate components of the storage and retrieval system **100**, for example, a location of a predetermined storage location and an appropriately sized case unit or case units for placement in the predetermined storage location. That case unit may be transferred into the storage and retrieval system **100** where a bot **110** delivers the case unit to the predetermined storage location. As a non-limiting example, the sensors **1710-1716** of the bots **110** may count slats **620L1**, **620L2** (FIG. 5A) and/or detect edges of case units on the storage shelves for dynamically positioning the bots for placing the case unit in the predetermined storage location. Dynamically positioning the bots **110** and/or the dynamic allocation of shelf storage space may allow for the positioning of case units having varying lengths in each storage bay **5000**, **5001** (FIGS. 14A and 14B) such that the use of the storage space is maximized. For example, FIG. 14A illustrates a storage bay **5000** divided into storage slots **S1-S4** as is done in conventional storage systems. The size of the storage slots **S1-S4** may be a fixed size dependent on a size of the largest case unit (e.g. case unit **5011**) to be stored on the shelf **600** of the storage bay **5000**. As can be seen in FIG. 14A, when case units **5010**, **5012**, **5013** of varying dimensions, which are smaller than case unit **5011**, are placed in a respective storage slot **S1**, **S2**, **S4** a significant portion of the storage bay capacity, as indicated by the shaded boxes, remains unused. In accordance with an exemplary embodiment, FIG. 14B illustrates a storage bay **5001** having dimensions substantially similar to storage bay **5000**. In FIG. 14B the case units **5010-5016** are placed on the shelf **600** using dynamic allocation. As can be seen in FIG. 14B, dynamically allocating the storage space allows placement of case units **5014-5016** on shelf **600** in addition to case units **5010-5013** (which are the same case units placed in storage bay **5000** described above) such that the unused storage space, as indicated by the hatched boxes, is less than the unused storage space using the fixed slots of FIG. 14A. FIG. 14C illustrates a side by side comparison of the unused storage space for the fixed slots and dynamic allocation storage described above. It is noted that the unused storage space of bay **5001** using dynamic allocation may be decreased even further by decreasing the amount of space between the case units **5010-5016** which may allow for placement of additional case units on the shelf **600**. As may be realized, as items are placed within the storage structure the open storage spaces may be analyzed, by for example the control server **120**, after each case unit placement and dynamically re-allocated according to a changed size of the open storage space so that additional case units having a size corresponding to (or less than) a size of the re-allocated storage space may be placed in the re-allocated storage space.

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It should be understood that the exemplary embodiments described herein may be used individually or in any suitable combination thereof. It should also be understood that the foregoing description is only illustrative of the embodiments. Various alternatives and modifications can be devised by those skilled in the art without departing from the embodiments. Accordingly, the present embodiments are intended to embrace all such alternatives, modifications and variances that fall within the scope of the appended claims.

What is claimed is:

1. An automated case unit storage system for handling case units that are adapted for being palletized for shipping to or from a storage facility, the automated case unit storage system comprising:

an array of multilevel storage racks having predefined storage areas at each rack level so that at least one corresponding predetermined storage area is disposed in a common level of each rack level;

a controller configured to effect dynamic allocation of case units of dissimilar sizes into dynamically allocated and sized storage areas of the at least one corresponding storage area on each rack level in the array of multilevel storage racks; and

an independent autonomous transport vehicle operatively connected to the controller, the independent autonomous transport vehicle being configured for independently traversing an aisle or deck within one level of the multilevel storage racks and for transferring the case units to or from the predefined storage areas, the independent autonomous transport vehicle including

an independent frame,

a support shelf adapted for holding at least one case unit thereon, the support shelf being movably connected to the independent frame so that the support shelf is movable between extended and retracted positions,

a drive system mounted to the independent frame, and guiding devices mounted to the independent frame;

where the independent autonomous transport vehicle is configured to effect dynamic allocation of case units of dissimilar sizes into the dynamically allocated storage areas so that a mix of the dissimilarly sized case units are each disposed by the autonomous transport vehicle into corresponding dissimilarly sized storage areas of the dynamically allocated storage areas of the common level of the at least one corresponding storage area of each rack level of the multilevel storage racks in the array of the multilevel storage racks.

2. The automated case unit storage system of claim 1, wherein the dynamic allocation of case units comprises the independent autonomous transport vehicle being configured to stop at a dynamically determined position along picking aisles of the array of multilevel storage racks for aligning at least a portion of the support shelf with a case unit or empty space located in the array of multilevel storage racks for effecting a transfer of at least one case unit between the support shelf and a storage area corresponding to one of the case unit or empty space.

3. The automated case unit storage system of claim 1, wherein the array of multilevel storage racks comprise a floor having tracked transport areas for guiding the independent autonomous transport vehicle through tracked and un-tracked transport areas, the independent autonomous transport vehicle being configured to transition between the tracked transport areas and the un-tracked transport areas, the guiding devices including at least one sensor configured to sense at least one feature of the un-tracked transport areas for contact-

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lessly guiding the independent autonomous transport vehicle in the un-tracked transport areas.

4. The automated case unit storage system of claim 1, wherein the predefined storage areas include slatted storage shelves having raised support surfaces separated by open channels, the guiding devices including sensors for detecting the raised support surfaces for locating the independent autonomous transport vehicle within the array of multilevel storage racks and effecting dynamic allocation of the case units in the predefined storage areas.

5. The automated case unit storage system of claim 4, wherein the support shelf includes extendable fingers configured to pass into the open channels for removing and placing case units on the slatted storage shelves.

6. The automated case unit storage system of claim 4, wherein the independent autonomous transport vehicle includes a lifting device for lifting and lowering the support shelf for transferring case units to or from the slatted storage shelves.

7. The automated case unit storage system of claim 1, wherein the independent frame has a first end and a second end, the independent autonomous transport vehicle further

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include a pair of individually operable drive wheels disposed at the first end and driven by the drive system and a pair of idler wheels disposed at the second end.

8. The automated case unit storage system of claim 7, wherein the independent autonomous transport vehicle further includes at least one caster disposed on the second end, the at least one caster being configured for extension and retraction, where extension of the caster raises the idler wheels off of a floor surface for allowing the independent autonomous transport vehicle to pivot about the drive wheels on the at least one caster.

9. The automated case unit storage system of claim 1, further comprising:

a substantially continuous lift configured to transport case units to predetermined levels of the array of multilevel storage racks, the substantially continuous lift comprising slatted transport shelves adapted for holding case units thereon, the independent autonomous transport vehicle being configured to directly or indirectly place or remove case units from the transport shelves of the substantially continuous lift.

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